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Wave Hindcast for Typhoons

By

P. S. SRIVASTAVA*

(Received November 13, 1963)

Abstract: Wave hindcast using WILSON'S method have been made for typhoon conditions. Values of significant wave heights and period so obtained have been compared with observed values and with hind-cast values using SVERDRUP-MUNK method. Reasons for the differences in calculated and recorded values have been discussed.

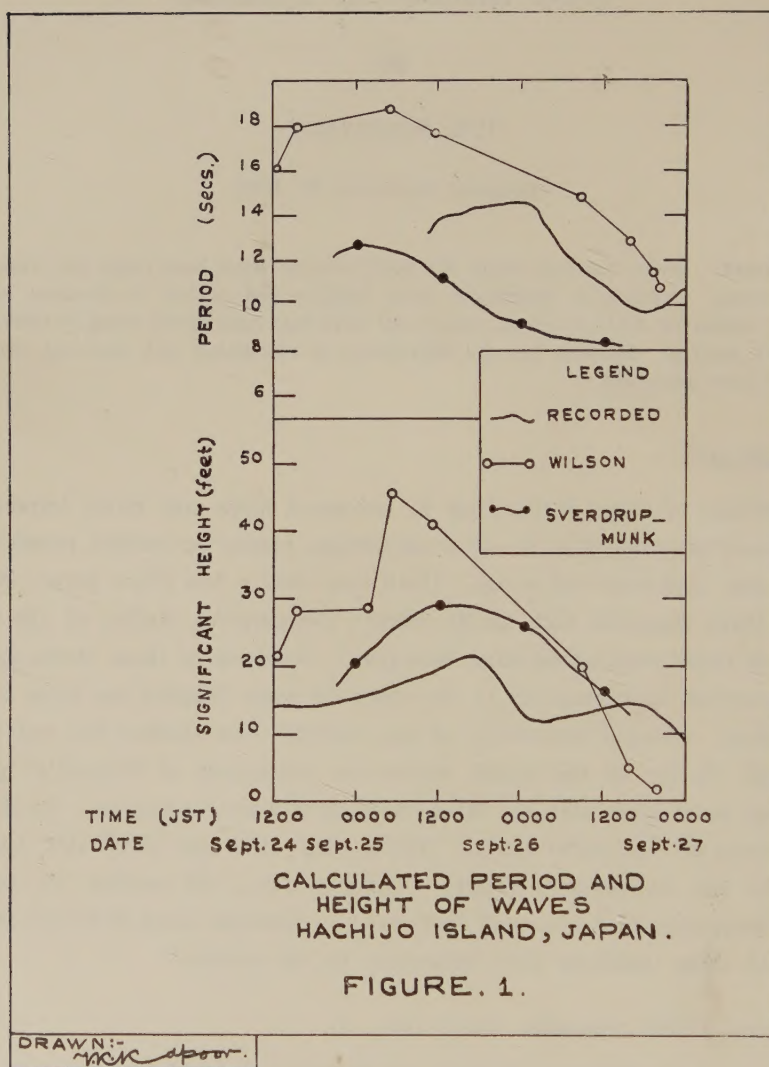
1. Introduction

Knowledge of wave forecasting is becoming more and more important due to its numerous application in naval operations, rescue operations, coastal engineering, erosion problems and so on. Until now only a few (New Jersey Nov. 6-7, 1953)¹⁾, (Point Arguello, Oct. 26-29, 1950)²⁾, comparative studies of the different methods of wave forecasting have been done. Analysis of these storm data show that the nearest approximation to the observed wave heights are those found by SM³⁾ method. General superiority of one method over another has not yet been established. So far as the author knows no comparison of WILSON'S⁴⁾ graphical method has been made with the other methods of wave forecasting. In this study two typhoons off the Japan's coast (TESS, Sep. 1953 and TRIX Oct. 1952) were chosen for the comparative study. Analysis using SM method for these two typhoons were done by UNOKI and NAKANO^{5,6)}. Analysis using WILSON'S procedure for both of these typhoons have been done by the author.⁷⁾

2. Typhoon TESS September 1953 (Fig. 1)

In the case of typhoons velocity, and direction of wind changes very rapidly, hence it is quite difficult to determine the mean wind velocity, fetch and direction uniquely. To avoid this difficulty UNOKI and NAKANO drew the wind-time diagram as suggested by DARBYSHIRE and then used SM method of forecasting the wave parameters. Their values of wave periods are lower than the recorded

* Present Address: Indian Naval Physical Laboratory, Cochin, India.



wave period while their values of significant height are higher than the recorded values.

To convert the geostrophic wind to surface wind UNOKI and NAKANO did not consider the stability of the air (personal communication KAJIURA). The consideration of the stability of air, in derivation of surface wind, brings about noticeable amount of change in the wind field. The author has redrawn the wind field using ARTHUR's⁹⁾ procedure.

The values of significant height and period based on WILSON's method are shown in Fig. 1. To consider refraction effect at the coast the author has used refraction diagrams of UNOKI and NAKANO. Maximum wave height obtained by WILSON's method is nearly twice the recorded maximum value. There can be different reasons for the discrepancy between the recorded and the calculated values:

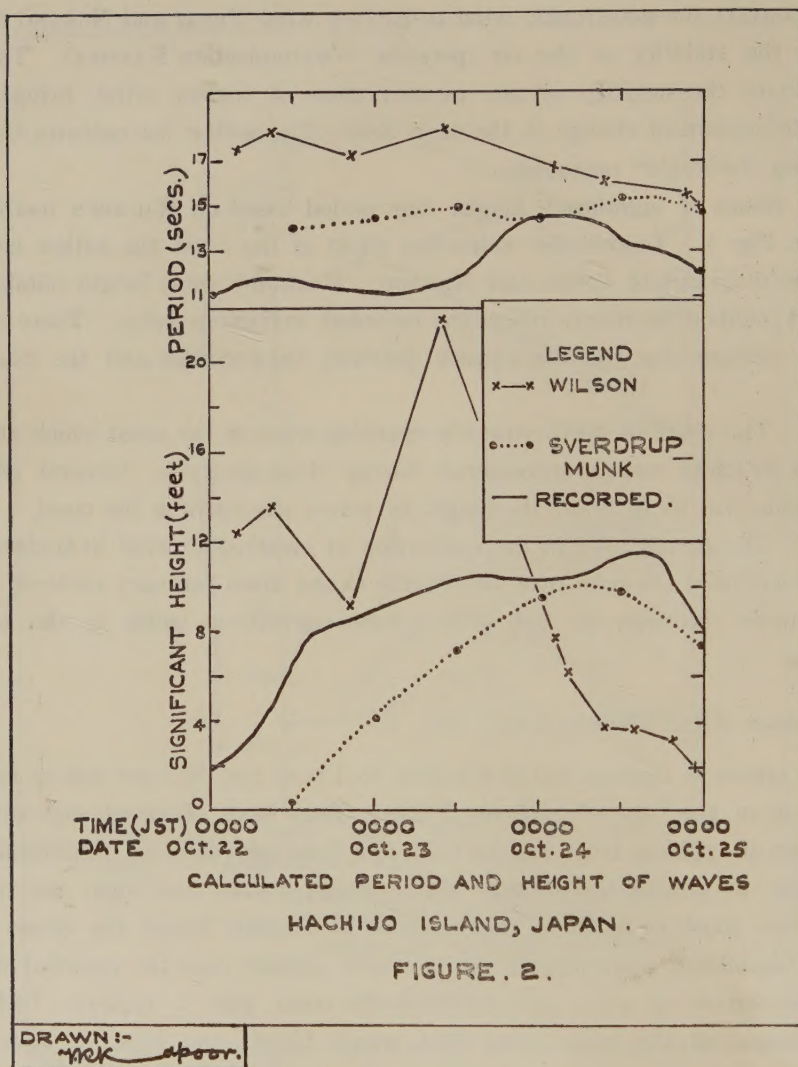
(1) The effect of north westerly opposing wind at the coast which at times exceeded 30 knots was not considered during those analysis. General effect of these winds will be to lower the height of waves approaching the coast.

(2) The curves used in the conversion of geostrophic wind to surface wind were drawn from the data over the Pacific Ocean from ordinary cyclonic storm. These curves probably do not give correct conversion factor in the case of typhoons.

3. Typhoon *TRIX* October 1952 (Fig. 2)

The errors in forecast values obtained by UNOKI and NAKANO was in opposite sense than in the case of typhoon *TESS*. They have observed that with the movement of typhoon from east to west, the forecast values of significant wave height are in general lower than the recorded values and when the typhoon moves from south to north in the direction of Hachijo Island the values of the forecast significant wave heights are generally greater than the recorded values.

In derivation of wave parameters at the coast, due to typhoon *TRIX* the author employed the same wind field, which UNOKI and NAKANO have used. The calculated significant wave heights, and periods obtained by the application of WILSON's method to this wind field are considerably at variance with the recorded values. The opposing wind in this case also sometimes exceeded 20 knots but its effect was not considered in the present analysis.



4. Conclusion

Significant wave heights and periods, calculated by WILSON's method, in general show a tendency towards a higher value than the recorded values. This discrepancy might be due to an error in the wind field or the forecasting curves. More analysis must be made before a definite conclusion can be reached in this regard. The present investigation although it represents only an indicative sample, has pointed out that further study in connection with existing method of wind field derivation be made.

The results of the present analysis seem to indicate that the simple method of SM give a better result.

The author suggests that some other method of taking the weighted mean of the calculated wave heights and periods, along different radial lines should be adopted, than simply taking an envelope curve. In his view an envelope curve is bound to give a higher value than the recorded ones, since in the later case waves of different heights and periods coming from different directions merge into one.

To get the weighted mean of the wave parameters a greater number of starting points should be chosen on the wind field, than has been done in the present analysis.

Acknowledgement: The author is sincerely grateful to Professor ROBERT O. REID, for his guidance and instructive suggestions.

The author takes this opportunity to thank Professors BASIL W. WILSON and MAURICE HALSTEAD for their valuable help during the analysis of data.

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Heat Flow Measurements during the JEDS-6 and JEDS-7 Cruises in 1963*

By

Seiya UYEDA** *Earthquake Research Institute,
University of Tokyo*

Masashi YASUI*** *Japan Meteorological Agency*

Takahiro SATO *Hydrographic Department*

Hideo AKAMATSU *Japan Meteorological Agency*

Kaoru KAWADA**** *Tokyo College of Science*

(Received march 9, 1964)

In 1963, terrestrial heat flow measurements were made at seven localities in the western Pacific during the cruises of JEDS-6 (the Japanese Expedition of Deep Seas) of M/S Ryofu-Maru, Japan Meteorological Agency, and of JEDS-7 of M/S Takuyo, Hydrographic Department, Maritime Safety Agency. The measurements were all taken off northeastern Honshu and southeast of Hokkaido. Together with the previous data,¹⁾ there are now 19 heat flow values in the Pacific off Japanese Islands.

The new heat flow stations are G1, G12, G202 taken in JEDS-6 and G'2, G'5, G'10, and G'11 taken in JEDS-7. The measurement of the bottom temperature gradient was made by means of the thermogradmeter developed by us.²⁾ The thermal conductivity of sediments obtained at JEDS-6 and JEDS-7 stations was measured by the needle method aboard ship¹⁾.

According to the plan of JEDS-6 cruise, it was intended to take about twenty measurements and to perform some tests of the smallprobe method similar to the one developed by the Lamont Geological Observatory Group.³⁾ It was also tried in JEDS-6 work to use a small (20 HP) hydrographic winch with a 2.43-4.27 mm tapered wire instead of the big winch (107 HP) with thick tapered wire for lowering the instruments. This was to reduce the time and labour for the operation great deal. Use of a hydrographic winch has been practiced by the Scripps

* JEDS Contribution No. 56.

** Now at Geophysical Institute, University of Tokyo

*** Now at Maizuru Marine Observatory, Maizuru

**** Now at Earthquake Research Institute, University of Tokyo

Institution Group, but it was something new to us. This proved quite successful at Station G-1, but unfortunately the instrument was lost at station G-3. At station G-3 the wire broke at the moment when the instrument came up and caught by the lower edge of the lead-man plat-form of the ship. This, however, was no fault of the small winch method itself and could have been avoided if handled more carefully. As we were left with only one spare instrument with a pressure case fitted to the small-probes, subsequent measurements had to be taken by it alone. To make the situation worse, the smallprobe method, though much improved than before,¹⁾ did not work. The probes, attached to a larger pipe as shown in Fig. 1, proved perfect but slight leak of water took place through the junctions of electrical leads with the pressure case. After several trials were made without success, the small-probe method was abandoned and the pressure case was repaired aboard ship to fit the original thicker probe. These affairs took so much time that only three successful measurements were possible in JEDS-6.

In JEDS-7 of M/S Takuyo, four more measurements were added also using a hydrographic winch. All through the work, no sonar pinger was available and the bottom contact was detected by means of a tension-gauge of the wire and by feeling with hand. The latter was found quite useful when the water depth is less than 3000 m say. But still the need for a sonar pinger is urgent because there were three cases the probe did not get the bottom.

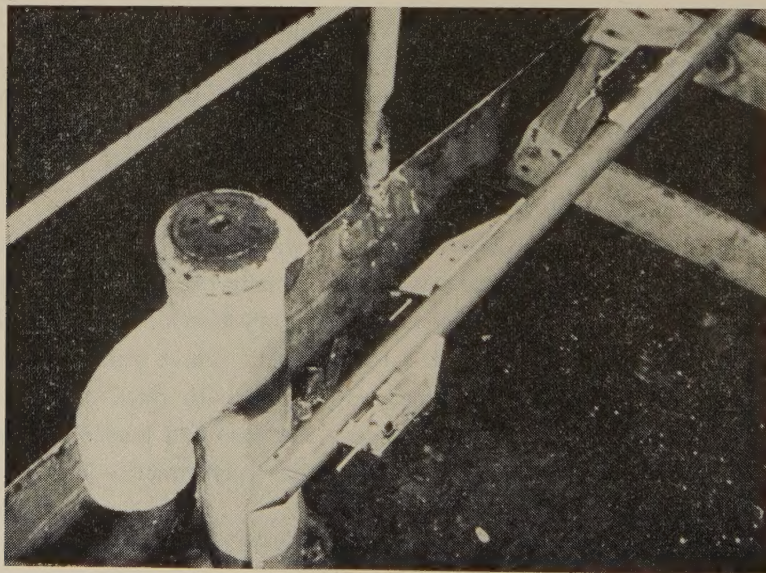


Fig. 1. (a)



Fig. 1. (b)

Some descriptions regarding the new stations are listed in Table 1. The new heat flow data are listed in Table 2 and shown in Fig. 2 together with the previous

Table 1.

Station	Date	Latitude (N)	Longitude (E)	Depth (m)	Time at surface (h,m)	Bottom contact time (h,m)	Duration in bottom (min)	Time at surface (h,m)	Wire re-ading at bottom contact (m)	Appa-ratus
G 1	May 9	40°02'	142°31'	810	08 35	09 52	21		798	R 1
G 12	May 23	43 26	148 15	5715	02 05	04 04	19	06 03	5473	R 2
G 202	June 8	40 28	142 59	1550	01 43	02 12	19	03 08	1584	R 2
G' 2	July 8	39 42	145 25	5315	22 40	23 29	21		5536	R 2
G' 5	July 13	40 24	145 40	5215	17 15	18 19		20 15	5325	R 2
G' 10	July 19	41 52	145 09	4435	22 45	23 45	16	01 10	4553	R 2
G' 11	July 21	41 02	146 00	5495	11 12	12 00	15	13 30	5621	R 2

Table 2.

Station	Latitude (N)	Longitude (E)	Water depth, (m)	Geothermal gradient, (°C/100 m)	Thermal conductivity, (10 ⁻³ cal/cm sec°C)	Terrestrial heat flow, (10 ⁻⁶ cal/cm ² sec)
G 1	40 02	142 31	810	7.02	1.75	1.26
G 12	43 26	148 15	5175	4.07	1.53	0.62
G 202	40 28	142 59	1550	4.64	2.16	1.00
G' 2	39 42	145 25	5315	6.10	1.82	1.11
G' 5	40 24	145 40	5215	3.44	1.67	0.58
G' 10	41 52	145 09	4435	3.56	1.80	0.64
G' 11	41 02	146 00	5495	5.68	2.44	1.38

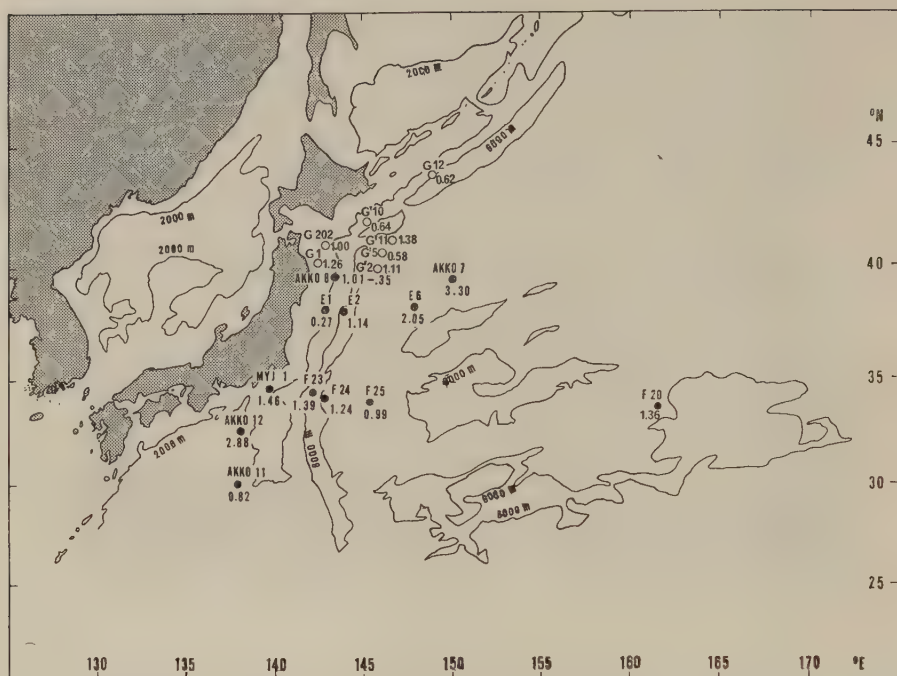


Fig. 2.

data. The new data were taken mainly in the southwestern end of the Kurile Trench. It may be seen in the figure that the area between the Kurile Trench and Hokkaido has low heat flow and this tendency is in good agreement with the general heat flow pattern so far obtained in and around Japan^{4), 5)}: the heat flow is high in the Japan Sea side of the Japanese Islands and low in the Pacific Ocean side. More measurements are planned in 1964.

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A Further Observation of a Deep Current in the East-North-East Sea of Torishima*

By

Tosio NAN-NITI *Meteorological Research Institute*

Hideo AKAMATSU *Japan Meteorological Agency*

Toshisuke NAKAI *Japan Meteorological Agency*

(Received Nov. 17, 1964)

Abstract: Series of 4-day measurements of deep current with neutrally-buoyant floats at 1000 m and 2000 m depths were made at $31^{\circ}37.5'N$, $143^{\circ}08.5'E$, at a distance of 300 km from Torishima. The mean values of each measurement were 4.7 ± 0.3 cm/sec toward 265° and 2.7 ± 0.2 cm/sec toward 168° true, and exhibited significant oscillations of about 23hr period. The measurement of 1000 m depth shows that there is the westward flowing water toward the Izu-Ogasawara submarine ridge, which may continue to the current observed formerly near the ridge (NAN-NITI, AKAMATSU, NAKAI, and FUJII, 1964), so it may cross the ridge through the narrow deep gap. On the other hand, the 2000 m depth current shows the south-south-eastward flowing water along the Japan Trench, or the Izu-Ogasawara ridge.

1. Introduction

A direct current measurement was already done near the southern end of Izu submarine ridge to ascertain whether the deep water will flow across the ridge or not (NAN-NITI et al., 1964). In the north-east direction of the former station, further observations were done to confirm the former result and to have a conclusion of the deep water flow across the ridge. The anchored buoy (NAN-NITI et al., 1964) was set at the location $31^{\circ}37.5'N$, $143^{\circ}08.5'E$, the depth was about 5500 m (Fig. 1). This bottom-area is fairly flat and its depth showed 5500 ± 50 m within a radius of 5 miles. The relative position of the float to the anchored buoy could be generally determined with an error of less than 0.23 miles, 0.4 km. (NAN-NITI et al., 1964)

2. Observations

During 21 st-24 th July 1964, a float was used in making the current measurement, loaded for 1000 m depth, and during 24 th-28 th July, another float was

* JEDS Contribution No. 58

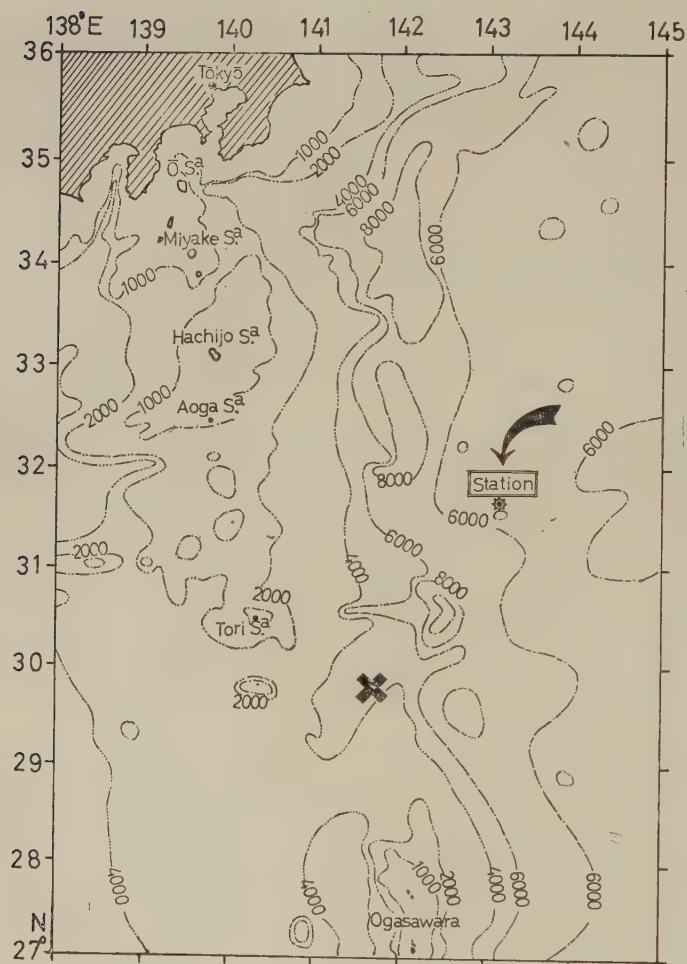


Fig. 1. Locality chart

▭: Station occupied in 1964

x: Station occupied in 1963

used for 2000 m depth. The floats were tracked for 74 hr in 1000 m depth and for 78 hr in 2000 m depth, their tracks are shown in Fig. 2. The abyssal plain had a mean depth of 5500 m, this deep towards the Izu ridge crosses its southern end (Fig. 1). The observed mean current of 1000 m depth flowed towards the ridge at 4.7 ± 0.3 cm/sec, on the other hand, 2000 m depth current flowed along the Japan Trench, or the Izu-Ogasawara ridge, at 2.7 ± 0.2 cm/sec.

The both observed tracks showed significant oscillations of about 23hr periodi-

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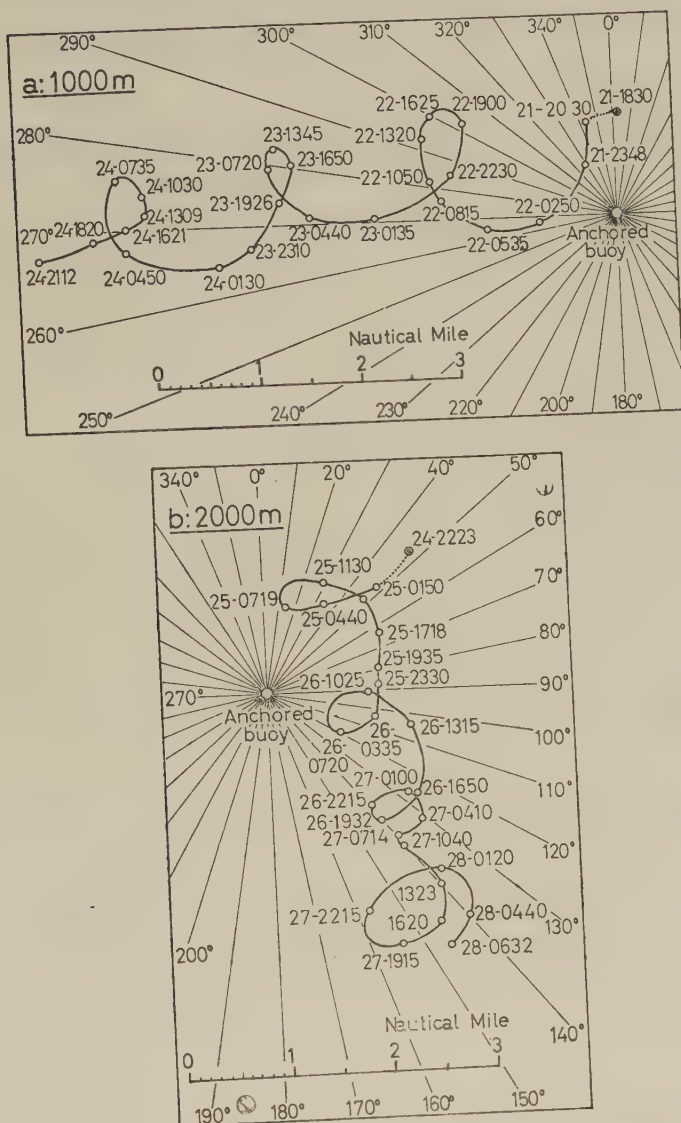


Fig. 2. Tracks of floats. Each dot represents a two or three-bearing fix whose circle of error is generally less than 100 m, the date and time of each fix is indicated.

- a: Depth 1000 m
- b: Depth 2000 m

city. Though KNAUSS (1962) and NAN-NITI et al. (1964) already followed neutrally-buoyant floats set at various depths, it is interested to note that unambiguous

internal oscillations were traced again with floats at 1000 m and 2000 m depths.

3. Results

The floats exhibited marked periodic motions and moved in clockwise orbits at speeds of 4.3–8.1 cm/sec for 1000 m depth current and 6.1–8.1 cm/sec for 2000 m

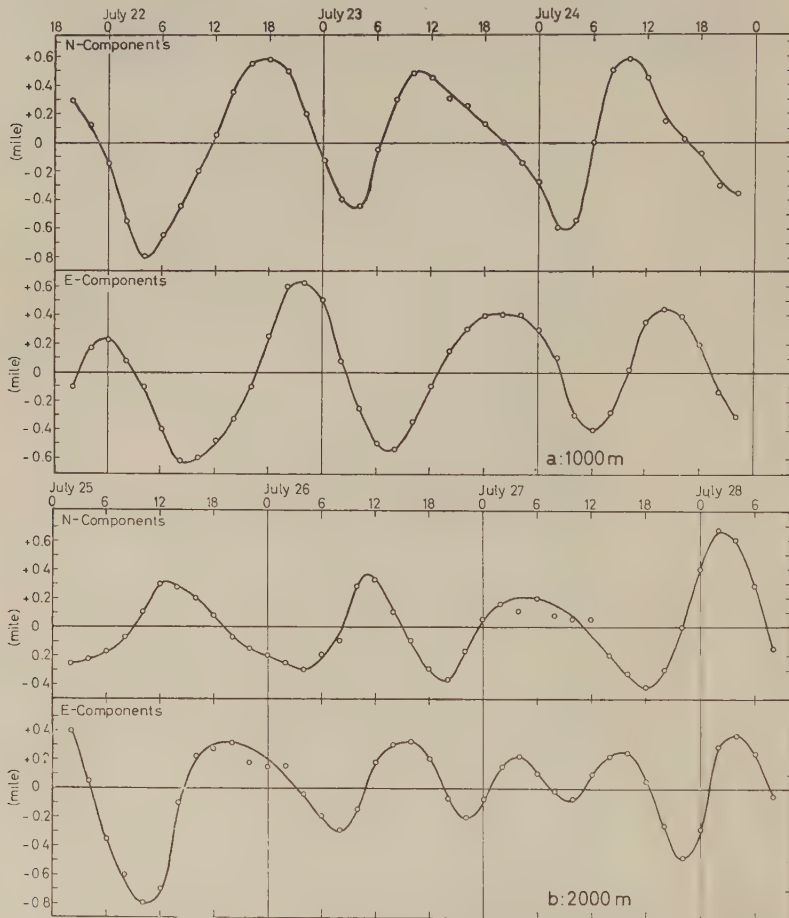
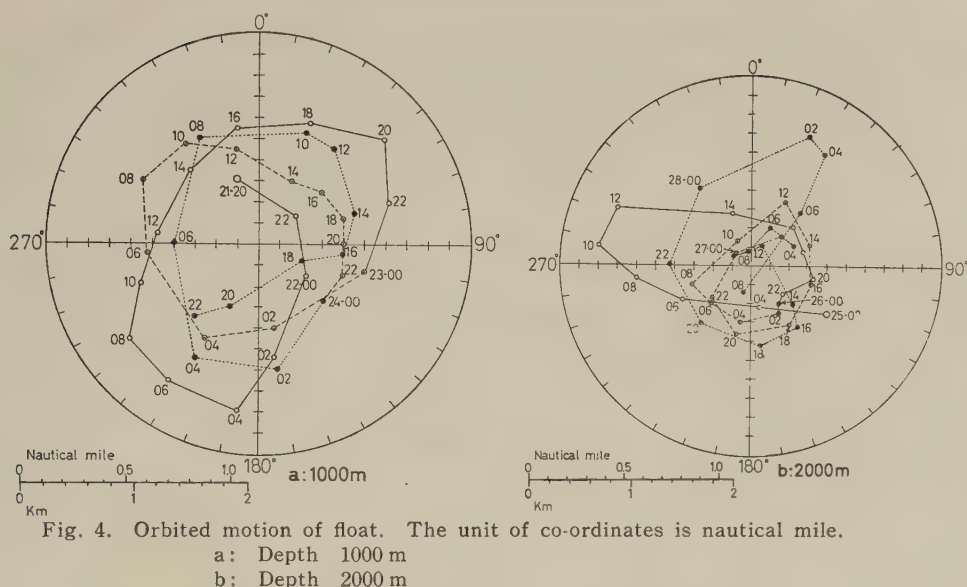


Fig. 3. East-west and north-south components of movement plotted against time. The unit of the ordinate axis is nautical mile; time is plotted along the abscissa.

a: Depth 1000 m
b: Depth 2000 m

depth, with a periodicity of approximately 23 hrs. The theoretical value of half-pendulum day at $31^{\circ}38'N$ latitude, the mean location of observation, is 22^h44^m . The inertia motion at 2000 m depth showed a fluctuation in its size. The dimen-

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sion of the elliptical orbit for 1000 m depth current is 930–1600 m of the major axis and 550–740 m of the minor one respectively, and the mean speed of orbital motion is about 6.6 cm/sec; next 930–1670 m of the major axis and 550–1200 m of the minor one and the mean speed of orbital motion is about 7.1 cm/sec for 2000 m depth current.

The translational components are obtained by least squares at 4.7 ± 0.3 cm/sec toward 265° for 1000 m depth and 2.7 ± 0.2 cm/sec toward 168° true for 2000 m depth. After these translational components have been removed, east-west and north-south components of movement plotted against time are shown in Fig. 3, and the orbital motions are shown in Fig. 4. The radius of the circular motion is about 930–1300 m as its speed is 7.0–9.9 cm/sec for 1000 m depth current, and the radius is about 550–750 m, speed is 4.2–5.7 cm/sec for 2000 m depth current.

4. Estimating of the depths of floats

Two or three bearings were taken from different ship's positions to decide a float's position in horizontal plane assuming the constant depth of the float to be 1000 m or 2000 m. Conversely, the scattering of bearings could estimate the depths of floats to be about 1000 ± 200 m and 2000 ± 300 m assuming the definite distances in horizontal plane between the ship and the floats.

By another method, the expected depths which the floats were made neutrally-buoyant by added weights were obtained to be 984 and 1995 m from observations

of temperature and salinity.

5. The method of computing the velocity profiles and volume transport

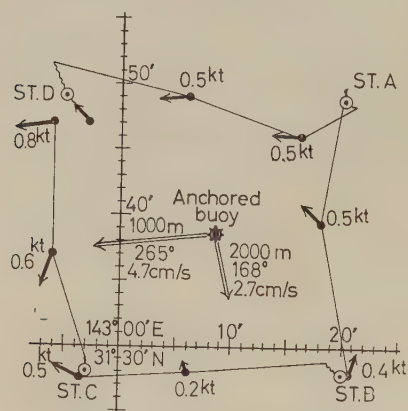


Fig. 5. Hydrographic stations bracketing the anchored buoy.

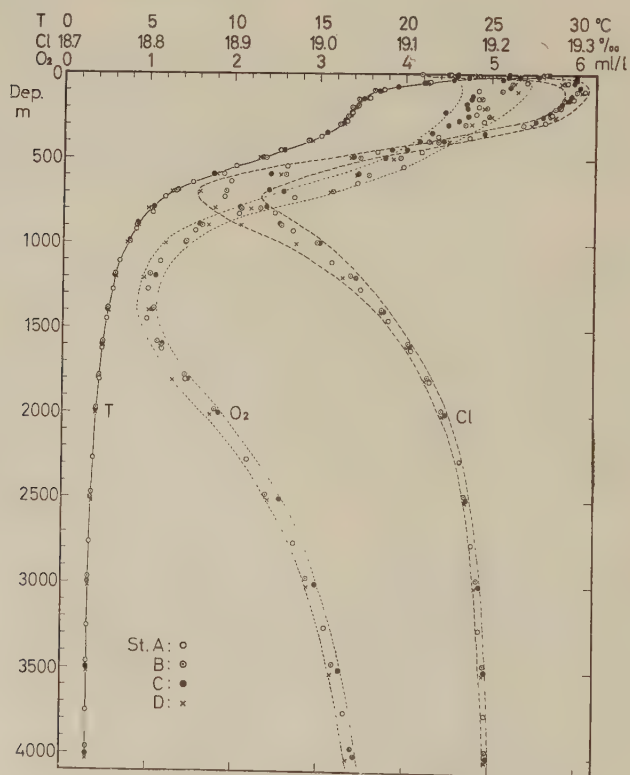


Fig. 6. Vertical distributions of temperature, chlorinity, dissolved oxygen.

At four hydrographic stations A, B, C, D, bracketing the anchored buoy, temperatures, chlorinities and quantities of dissolved oxygen were observed (Figs. 5, 6). The pairs of stations AD and BC were taken parallel with the direction of 1000 m float. Using the direct-observed velocity as a reference, the dynamically calculated velocities of 1700 m depth between the pairs of stations AB, BC, CD, and DA must be zero as the each calculated velocity of 1000 m depth must be 4.7 cm/sec; and they may be expected to be almost zero between AD also BC assuming that the direct-observed velocity remained unchanged in the vicinity of the anchored station. On the basis of this measurement, the depth of no motion, 1700 m, could be determined. Fig. 7a shows the geostrophic currents in each section calculated from each pair of stations. The surface current observations with the GEK are shown in Fig. 5, they are the same values obtained by the present geostrophic calculations.

The volume transports were computed simply according to $Area \times Velocity$.

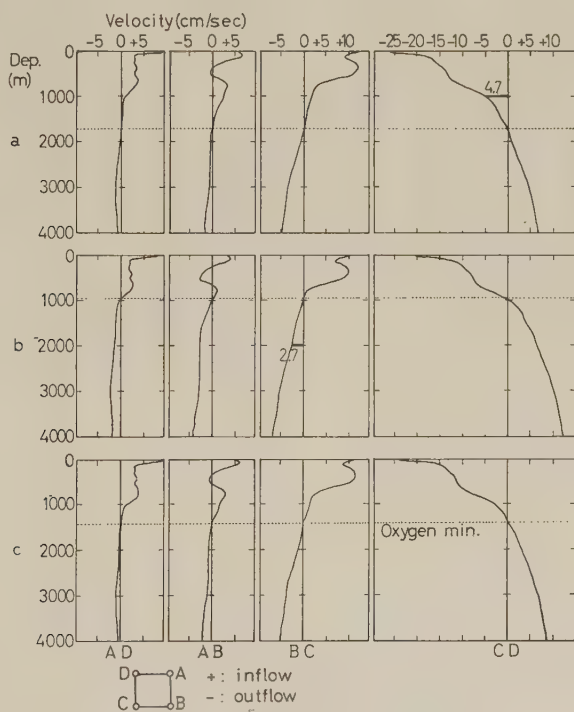


Fig. 7. Geostrophic currents in each section.
a: Referred to 1700 m
b: Referred to 950 m
c: Referred to 1400 m

They take some different values by some different assumption of depths of no motion, (Table 1). The volume transports referred to the depth of 1700 m (Table 1a) show that the income volume transports, through the sections AB, BC, and DA are approximately same to the outgoing volume transport through the section CD. Also we have the volume transports referred to the depth of 950 m (Table 1b), as the velocity of 2000 m depth of section BC must be 2.7 cm/sec; and values referred to the oxygen minimum of 1400 m depth (Table 1c).

Table 1. Volume transports referred to each assumed depth of no motion

a. Referred to the depth of 1700 m		
Section	Volume transport ($\times 10^6$ m ³ /sec)	
AD	+1.39	-0.55
AB	+1.25	-0.64
BC	+3.01	-2.21
Total	(+5.65)	(-3.40)
CD	-5.67	+3.43
b. Referred to the depth of 950 m		
AD	+0.84	-1.97
AB	+0.07	-3.17
BC	+2.07	-4.23
Total	(+2.98)	(-9.37)
CD	-2.94	+9.30
c. Referred to the Oxygen minimum at the depth of 1400 m		
AD	+1.37	-0.58
AB	+0.88	-1.24
BC	+2.73	-2.65
Total	(+4.98)	(-4.47)
CD	-4.42	+5.47

All these values of income volume transports through the sections AB, BC, and AD are approximately same to the outgoing volume transports through the section CD. But in the case of b, the east-north-east direction transport is larger than the west-south-west transport, this is a strange direction for the Kuroshio countercurrent. So we think the assumed depths of no motion in the cases a or c are better than in the case b and the depth of no motion may be about 1400-1700 m. The water deeper than this layer may flow towards south-south-

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east, along the Japan Trench. The formerly observed deep current (TAKENOUTI, NAN-NITI and YASUI, 1962) flowed southward along the Japan trench and it is reasonable to think that its southern part was observed by this measurement. The upper water than the 1500 m depth makes a part of the gyre of Kuroshio countercurrent and crosses the ridge.

6. *Conclusion*

With the results obtained by this and the former observations (NAN-NITI et al., 1964), we have a following conclusion that there are the westward flowing water from the surface to about 1500 m level, which will cross the Izu-Ogasawara submarine ridge, and the south-south-eastward under current below this, which will flow along the Japan Trench or the Izu-Ogasawara ridge. They exhibited significant inertia oscillations.

Acknowledgements: The authors wish to express their sincere appreciation for the cooperation of member of observation and the crew on board the R. S. Ryofu-Marui.

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A Typical Hydrographic Section of the Kuroshio Extension⁽¹⁾

By

Jotaro MASUZAWA

Japan Meteorological Agency

(Received Nov. 18, 1964)

Abstract: A typical section of temperature, salinity, oxygen, specific volume, and current across the Kuroshio Extension is presented from the hydrographic observation made by the R/V Ryofu-Maru along 144°E long. in November 1959. The geostrophic flux in each class of water characteristics carried by the current is computed, and three important waters of the Kuroshio Extension are distinguished, the surface mixed water, the 17°-water and the intermediate water.

1. Introduction

The term *Kuroshio Extension* has been proposed by SVERDRUP et al. (1942) in reference to the strong current east of Japan, representing the direct continuation of the Kuroshio south of Japan. Then, the term *Kurōshio* has been used to represent the western boundary current flowing generally along the continental slope from Taiwan to the south coast of Japan as far as 35°N lat. According to ISELIN's (1936) nomenclature of the Gulf Stream System, the Kuroshio is the counterpart of the Florida Current in the North Atlantic, and the Kuroshio Extension is that of the Gulf Stream. The Kuroshio leaves the coast of Japan off Cape Inubo-zaki (36°N lat.), which corresponds to Cape Hatteras of North America, and then it flows nearly east. The Kuroshio Extension encounters east of Honshu with the Oyashio flowing southward along the east coast of Hokkaido and North Honshu. A big difference of submarine topography between the Gulf Stream region and the Kuroshio Extension region is that north of the Kuroshio Extension is not seen a continental shelf as wide as north of the Gulf Stream from Cape Hatteras to the southern tip of Grand Banks.

The Kuroshio Extension is one of the most interesting subjects of the North Pacific Oceanography, and a large number of observations in this region have

⁽¹⁾ Currents and Water Characteristics of the Kuroshio System [XII]

been carried out by Japan and USSR. A lot of hydrographic sections across the Kuroshio Extension have been made by many ships, especially by the R/V Ryofu-Maru, Japan Meteorological Agency (JMA) since 1954. Unfortunately, however, most of those sections are too short, too shallow, or too coarse-stationed to delineate the whole width of the Kuroshio Extension. A special cruise was done by the Ryofu-Maru in November 13-15, 1959 to make a deep and long hydrographic section along 144°E long., as distant as 150 miles from the coast. A preliminary report of the results from this cruise has been published (JMA, Oceanographical Section, 1960). The results from the more careful analysis of the data might be useful to get an idea of typical hydrographic section of the Kuroshio Extension.

2. Surface current

In November 1959, the Kuroshio east of Cape Inubo-zaki flowed to the north-

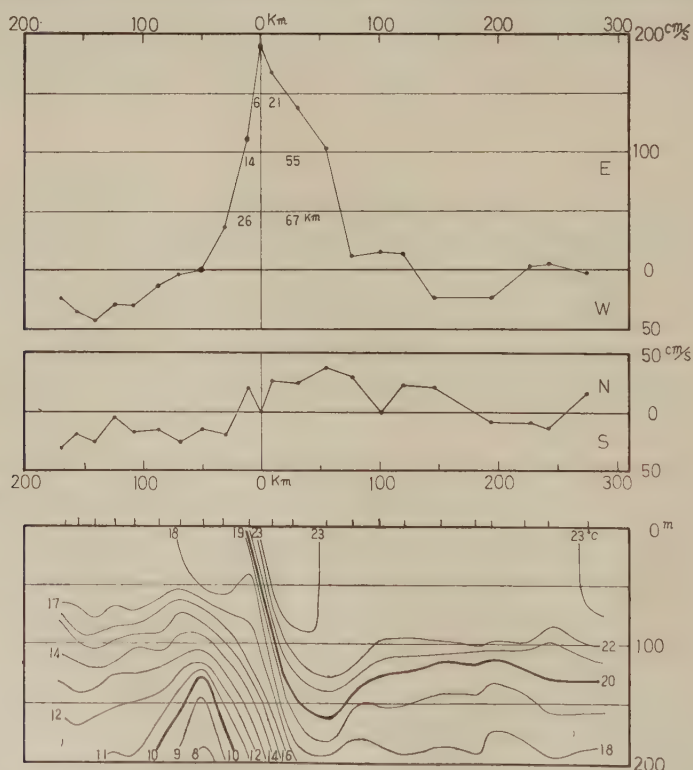


Fig. 1. Profiles of the east-west components (upper) and of the north-south components (middle) of surface velocity measured by GEK, and the BT section (lower: vertical exaggeration, 1000) along 144°E long. in November 13-15, 1959.

east, and the current-axis at 144°E long. was located around $36^{\circ}45'\text{N}$ lat., the current-direction there being due east. Therefore, the hydrographic section along 144°E long. is suitable to show the cross-current structure of the Kuroshio Extension.

Since surface currents were measured by GEK at intervals of about ten or twenty kilometers, the surface-current profile across the Kuroshio Extension cannot be exactly determined. The profile of east-west component of surface-velocity is asymmetric with the current-maximum (Fig. 1). The belt with high speed, say more than 100 cm/s, on the anticyclonic shear zone (south of the current-maximum) is about three times as wide as on the cyclonic shear zone (north of the current-maximum). As well known, the cyclonic horizontal shear is larger than the anticyclonic horizontal shear, and the former sometimes exceeds the Coriolis parameter (MASUZAWA, 1958; Von ARX, 1952).

Individual values of the north-south (cross-current) component of surface-velocity by GEK are not reliable enough to be discussed in details, but it may be seen in Fig. 1 that the cross-current components are north at the south side in contrast with south at the north side. A similar profile of cross-current velocity has been shown by KAWAI (1955). From this profile, the magnitude of horizontal gradient of cross-current velocity may be estimated to be about $0.5 \times 10^{-5} \text{ sec}^{-1}$, which might give an approximate magnitude of the horizontal divergence or convergence.

3. Geostrophic structure

The curvature of streamline is not so large on the section, and the current field is approximately in geostrophic equilibrium. The mass field has been represented by thermosteric anomaly (Fig. 2).

In the surface layer of the main part of the current (between St. 1296 and 1298) can be found a lightest water (thermosteric anomaly, more than 400 cl/ton), which is the warm core mentioned later. Below the water, the isanosteric surfaces (surfaces of uniform thermosteric-anomaly) slope down from north to south, the maximum slope estimated from Fig. 2 being about 0.3×10^{-2} . However, if stations were more closely spaced in the current, the maximum slope of isanosteric surface could be nearly 1:100 as estimated from the detailed sections of the Gulf Stream (WORTHINGTON, 1954).

The horizontal gradient of specific volume is significantly detectable at 2000 m or deeper in the strong current, so the vertical shear of geostrophic velocity is

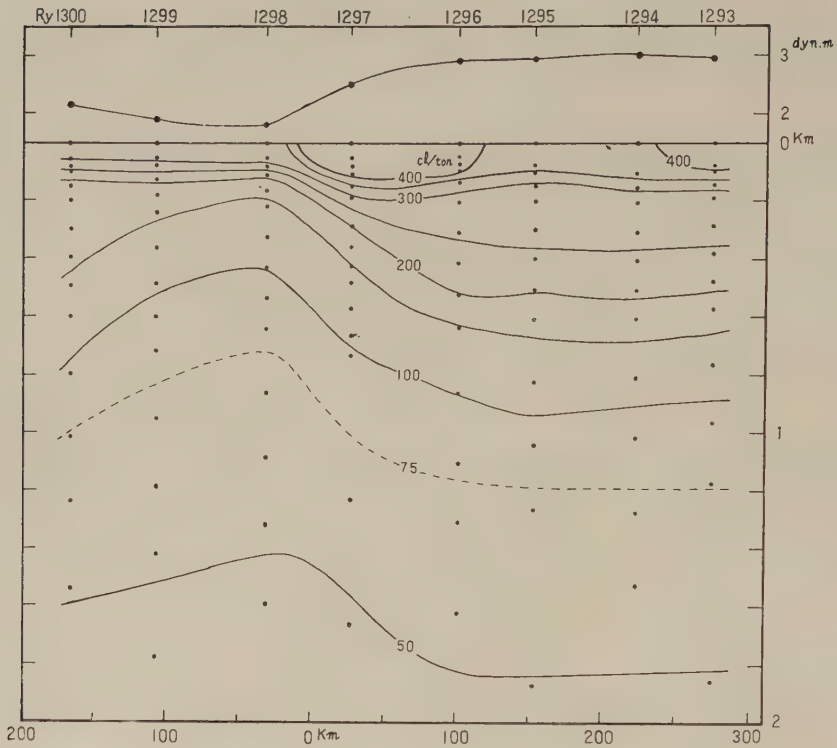


Fig. 2. Thermobaric-anomaly section (vertical exaggeration, 200) and the geopotential anomaly at the sea surface referred to 2000 m.

not negligibly small in the deep layer. In the present paper, for simplicity, the hydrostatic or geostrophic computation has been made from the reference level of 2000 m. The geopotential at the sea surface is shown on the top of Fig. 2. In the width (St. 1296-1298) of strong current, the horizontal gradient of geopotential (pressure) at the sea surface is about $10^{-2} \text{ cm} \cdot \text{sec}^{-2} (\text{g} \cdot \text{cm}^{-2} \cdot \text{sec}^{-2})$, that is, the slope of sea surface is about 10^{-5} .

The geopotential difference between these two stations decreases linearly with depth from surface to 500 m, where the geopotential difference is as much as 40% of that at sea surface. The decrease with depth is gradual below 500 m (Fig. 3), the difference at 1000 m is as much as 13% of that at sea surface. The vertical distribution of geopotential difference gives the vertical profile of average geostrophic-velocity of the Kuroshio.

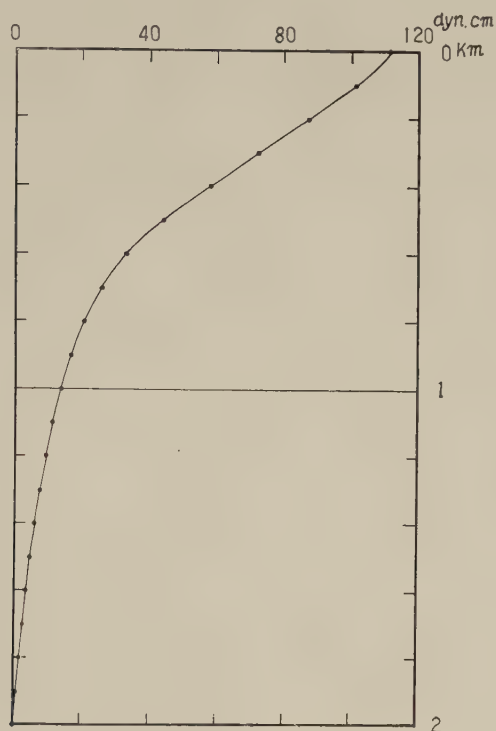


Fig. 3. Vertical profile of the geopotential difference between St. 1296 and St. 1298.

4. Thermal structure

The surface mixed layer, nearly isothermal, in the BT section is as thick as 90 m south of the current-maximum and 60 m north of it. The warm core which is defined as a portion warmer than outside of it at a given level, is located in the upper 200 m layer just south of the current-maximum and it is as wide as 70 km. The northern edge of warm core forms a well-defined frontal surface, which slope may be more than 0.5×10^{-2} . The current-maximum at each level might be located on the frontal surface. That is, the current-maximum may shift south with depth, as observed in the Gulf Stream (VON ARX, 1952). To the north of the current-axis, the so-called *inner cold water* (KAWAI, 1955; MASUZAWA, 1956) can be found in the lower layer below 50 m (Fig. 1, 4).

The center of main thermocline ($6-16^{\circ}\text{C}$) slopes down from 100 m at the northern edge of the Kuroshio to 600 m at the southern edge. The main thermo-

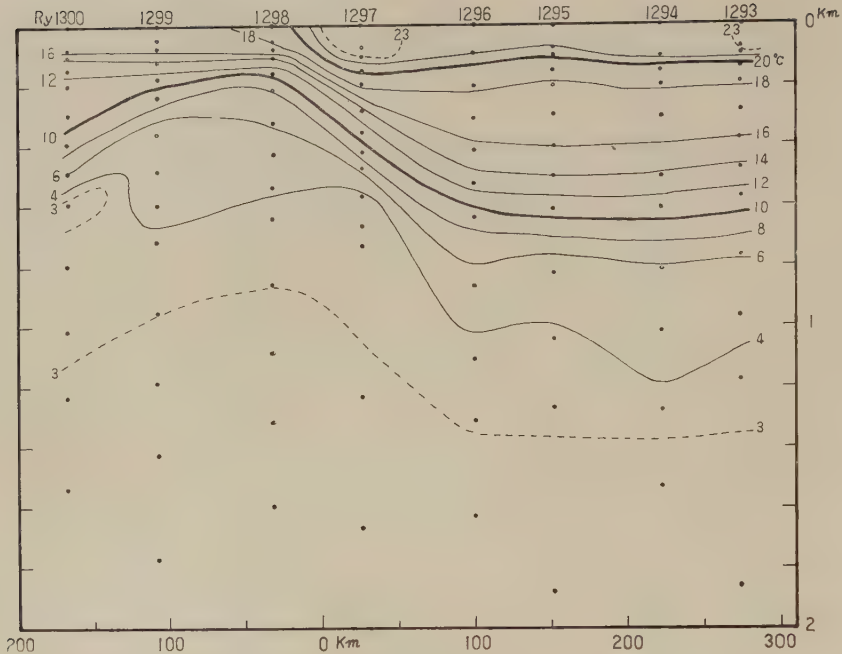


Fig. 4. Temperature section (vertical exaggeration, 200).

cline of the subtropical North Pacific is generally 200 m or 300 m shallower than that of the subtropical North Atlantic.

There is a nearly isothermal layer (16–18°C) between the surface mixed layer and the main thermocline. The water is in the layer of 200 m to 400 m south of the Kuroshio, and the vertical shrinking of it is noticeable in the high-velocity part of the Kuroshio. This characteristic water ($T=17^{\circ}\text{C}$, $S=34.8^{\circ}/_{00}$, $\delta_T=260$ cl/ton) is one of the most dominant water characteristics in the upper 1000 m layer of the subtropical western North Pacific. This is the counterpart of the 18° water in the North Atlantic (WORTHINGTON, 1959), and it may be important for the dynamics of the Kuroshio (STOMMEL, 1958).

5. Intermediate water

A salinity-minimum layer can be found immediately beneath the thermocline (Fig. 5). This is the North Pacific Intermediate Water which is found all over the subtropical North Pacific, its core being on the isanosteric surface of 120–130 cl/ton. The intermediate water which salinity is less than 34.0‰ has been never found in the section of the Kuroshio south of Japan. This relatively fresh in-

J. Masuzawa: A Typical Hydrographic Section of the Kuroshio Extension

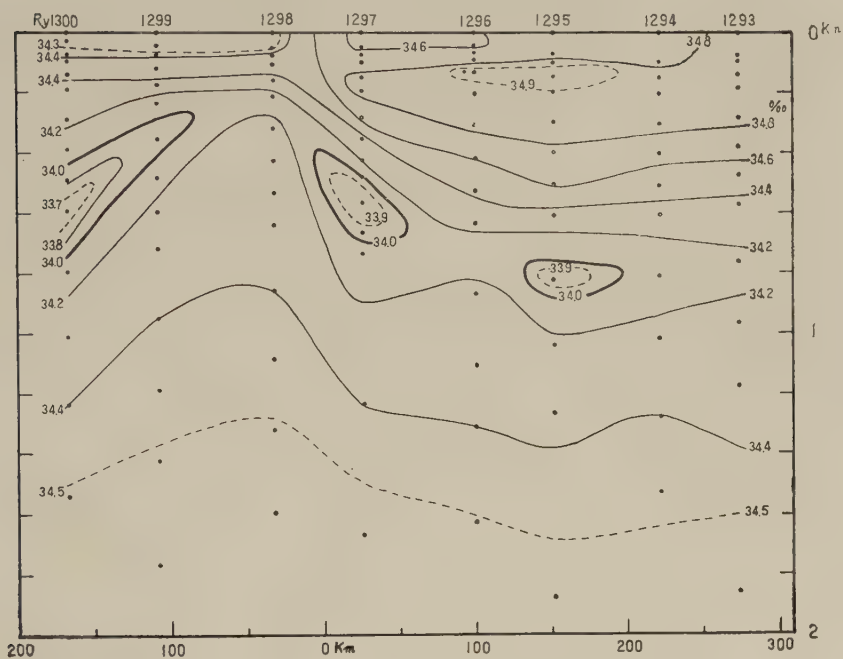


Fig. 5. Salinity section (vertical exaggeration, 200).

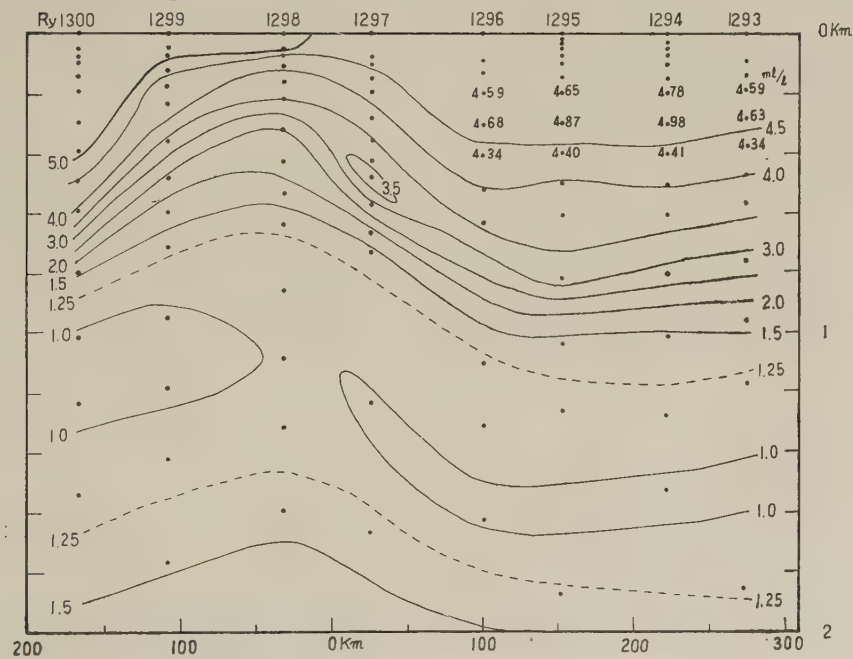


Fig. 6. Oxygen section (vertical exaggeration, 200).

intermediate water comes from the Oyashio region. This can be partly justified by the distribution of oxygen (Fig. 6, 7). Such a remarkably less-saline intermediate water like this can be found in the sections of the Gulf Stream east of

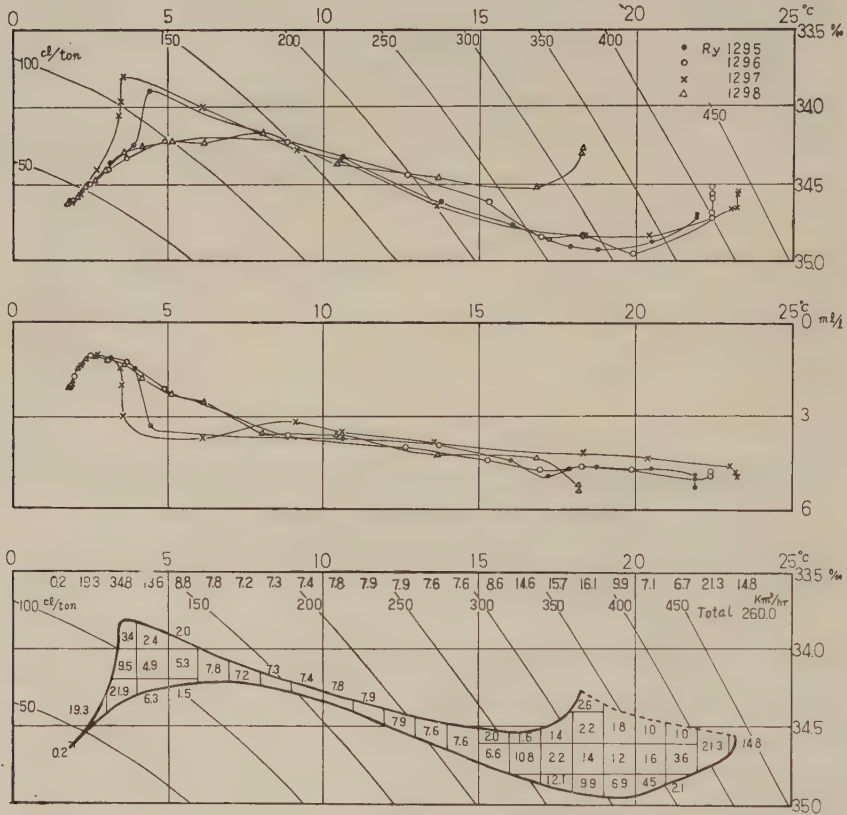


Fig. 7. Temperature-salinity curves (upper), temperature-oxygen curves (middle) and geostrophic fluxes (km^3/hr) on the temperature-salinity diagram.

57°W long. (FUGLISTER, 1963). Some of these fresh intermediate waters form a definite temperature-minimum, salinity-minimum, and oxygen-maximum in the section of the Kuroshio Extension (MASUZAWA, 1957).

The water characteristics of the intermediate water of the Kuroshio Extension might be changed considerably in travelling downstream from west to east probably by horizontal mixing. The lower part of the salinity minimum layer is bounded by the oxygen minimum layer which is in the range of thermosteric anomaly 50 to 80 cl/ton , the minimum oxygen-content being about 1 ml/l .

6. Flux of water characteristics

The geostrophic flux of the Kuroshio (between St. 1295 and 1298) has been computed assuming to be motionless at 2000 m. The total flux ($260 \text{ km}^3/\text{hr}$, $72 \times 10^6 \text{ m}^3/\text{s}$) is rather less than the Gulf Stream flux ($76-93 \times 10^6 \text{ m}^3/\text{s}$), which was computed by ISELIN (1940) based on the same assumption. The Kuroshio Extension might be supposed to extend beyond 2000 m nearly to the bottom, as observed in the Gulf Stream east of Cape Hatteras (FUGLISTER, 1963). The actual value of total flux might be much greater than $260 \text{ km}^3/\text{hr}$.

The geostrophic flux through the section between two adjacent stations has been computed every 50 m thickness in the upper 1000 m layer, and every 100 m in the lower 1000 m layer. Each flux computed in this way is divided into each class of water characteristics with temperature range of 1°C and with salinity range of 0.2‰ . The area of each class in the section is estimated from the temperature section which is overlapped by the salinity section. Both isotherms and isosalines in the section have been drawn such that the temperature-salinity relations of all points in this section fall within the envelope of observed temperature-salinity curves (Fig. 7).

Three outstanding modes can be noted in the distribution of flux on the temperature-salinity diagram. The one mode forms the surface mixed layer ($22-24^\circ\text{C}$), and its flux ($36.1 \text{ km}^3/\text{hr}$) is as much as 14% of the total flux. The other mode is seen in the layer of $16-19^\circ\text{C}$, centered around 17.5°C , 34.8‰ , and its flux ($46.4 \text{ km}^3/\text{hr}$) is as much as 18% of the total flux. The third mode centered at 3.5°C forms the intermediate water and the upper deep water. The flux of this mode much depends on the choice of reference level in geostrophic computation. It may be sure, however, that the large amount of the intermediate water forms the fairly large part of the total flux of the Kuroshio Extension.

The distribution of flux against temperature is uniform in the main thermocline ($6-15^\circ\text{C}$) between the second mode and the third mode.

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Newly-built M. R. V. Seifu Maru

By

Masashi YASUI

Maizuru Marine Observatory

(Received Nov. 25, 1964)

Seifu Maru is a newly-built oceanographic research vessel belonging to Maizuru Marine Observatory. Her facilities and specifics were decided and designed in full consideration of the dimension of the Sea of Japan, because her errand is mainly aimed at oceanographic studies of the Sea. She is on service since April 1964. The results of expeditions shall be successively published hereafter.

The characteristics of M. R. V. Seifu Maru is as follows:

Particulars:

Length overall	48.50 m	Length between perpendiculars	44.00 m
Breadth, moulded	7.80 m	Depth, moulded	3.80 m
Full loaded draft	2.81 m	Gross tonnage	355.0 tons
Trial speed	11.96 kt	Service speed	11.0 kt
Cruising range	8.400 miles	25 days	
Fuel oil tank	111.67 tons	Fresh water tank	92.72 tons
Provision refrigerator	5 m ³		
Complement			
Officer	6 rooms	10 berthes	
Crew		16 berthes	
Scientist	5 rooms	15 berthes	

Keellaid: July, 1963

Launching: November, 1963

Delivered: March, 1964

Main engine: 4 cycle super-charged diesel engine
(Fuji Diesel, 6 SD 30 H type) 1 set
Normal output; 552 H. P. 342 RPM.
Maximum output; 650 H. P. 360 RPM.

Propeller: Single, 4 braded, aerofoil type.

Generator:	Main generator; 60 c/s AC 50 KVA 225 V	2 set
	Diesel; 70 P. H. 900 RPM.	
Special facility:	A water-jet nozzle, turning round in gear with steering, just behind the rudder for gyration and dead-slow sailing.	
Echo-sounder:	Frequency 13.5 Kc/s & 200 Kc/s` switch system,	
	Out put; 1 KW 1 KW	
	Half-diminishing angle; 13° 30°	
	Maximum range; 4000 m 400 m	

Wells, in which transducers are installed, are juttred out beneath the hull and covered with bubbleguard like snow-plows turned upside-down.

Research winches:

Deep sea winch;	complex motor* system 15 KW (A. C)	
	1,200 Kg×60 m/min. (300 m/min at no load)	
	wire; 7,000 m×5.5 mm (breaking strength; 2,200 Kg)	
Hydrographic winch;	variable-speed commutator motor system	
	5.5 KW (A. C)	
	400 Kg×60 m/min (maximum speed; 130 m/min)	
	wire; 3,000 m×3.0 mm (b. s; 855 Kg)	
BT winch:	variable-speed commutator moter system	
	2.2 KW (A. C)	
	160 Kg×60 m/min (maximun; 120 m/min)	
	wire; 1,000 m×2.1 mm (b. s; 410 Kg)	

Laboratory space:

Deck laboratory;	sheltered; 11.5 m ²
	unsheltered; 18.0 m ²
Laboratory;	full-airconditioned (at 20°C); 2.7 m ²
	heating only; 23.5 m ²

Equipment and apparatus regularly embarked:

Nansen's water bottle:	1.2 l type; 30
	2.0 l type; 10
Reversing thermometer:	Nonprotected; 46
	Protected; 23

GEK 1 set.

*A sort of commutator motors (A. C.) which has two characteristics, of induction and series motor, and be changed freely and instantaneously.

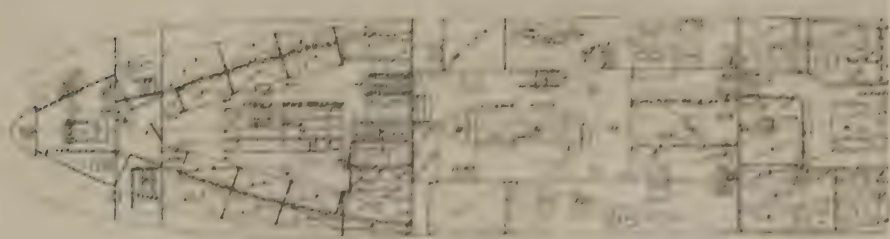
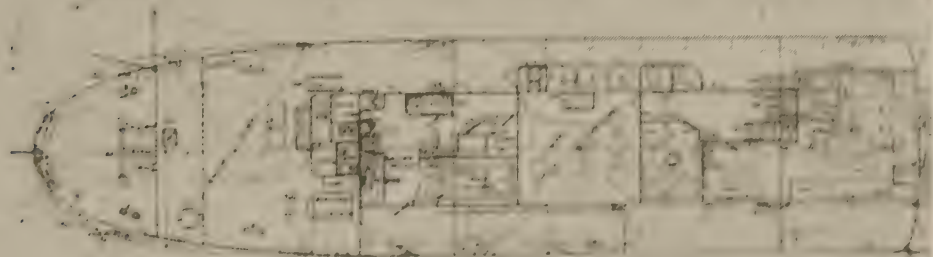
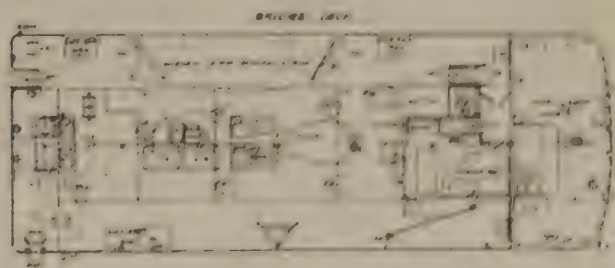
M. Yasui: Newly-built M. R. V. Seifu Maru

Bathythermograph	4 set.	
BT-record reader	1 set.	
Thermograd-meter for bottom sediment		2 set.
Heat-conductivity meter for bottom sediment		1 set.
Nonmagnetic piston-core sampler		2 set.
Inductively coupled salinometer		1 set.
Photoelectric colorimeter (Recording system)		1 set.
pH meter		1 set.
Piston burette for analysis of dissolved oxygen		1 set.
Proton-processing geomagnetmeter (towing system)		1 set.
Hauling nets for plankton collection		various.
Ordinary maritime meteorological instrument		various.



SEIFU MA

GENERAL ARRANG

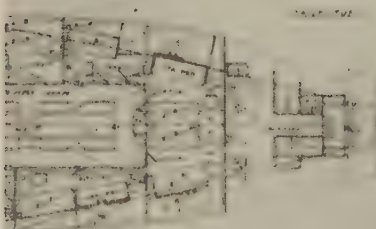
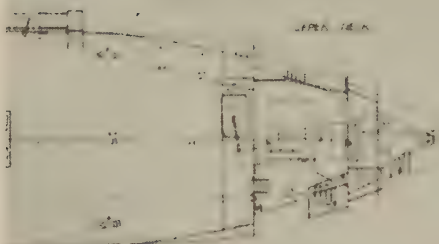
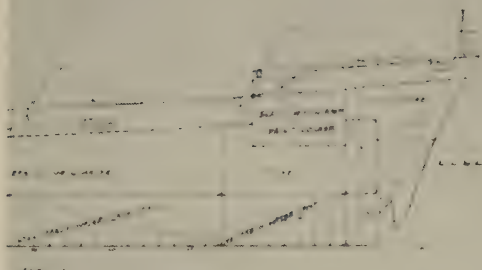


RU GEMENT

PRINCIPAL PARTICULARS	
LENGTH	14.00
BREADTH	3.30
DEPTH	3.80
DR. (MIL. L. M. L. A. T. T. M.)	4.0
WEIGHT (TONNAGE)	135.00
SERVICE (MND)	1.0
MAX. ENGINE	2.000
UNIKUT (MND)	1.0

COMPLEMENT

OFFICER
- RCM
OBSERVER



Oceanic Turbulence

By

Tosio NAN-NITI

Meteorological Research Institute

(Received Dec. 10, 1964)

Abstract: A relationship between rate of energy dissipation and scale of horizontal turbulence phenomena in the sea has been found which supports an exponent 1.19 of diffusion coefficient (OKUBO, 1962) instead of $4/3$ as previously advanced (RICHARDSON and STOMMEL, 1948, 1949).

Some oceanic phenomena are explained as the results of turbulence since these phenomena are created by the turbulent flow. They are formulated in order of the scale and the lifetime of turbulence.

1. Introduction: Recapitulation of the “ $4/3$ law”

RICHARDSON and STOMMEL (1948), and STOMMEL (1949) have shown that the coefficient of diffusion, K , of the particles, freely floating on the surface of the water is described approximately by the so called “ $4/3$ law”

$$K(l) = al^{4/3}, \quad (1)$$

where l denotes the scale of the phenomena (the distance between the particles) and a is the coefficient of proportionality.

The rate of dissipation of turbulent energy ε is linked with the coefficient of proportionality a in the “ $4/3$ law” by the relationship (KOLMOGOROV 1941, OBUKHOV 1941),

$$a = c\varepsilon^{1/3}, \quad (2)$$

where c is a universal dimensionless constant.

OZMIDOV (1960) suggests that the rate of energy dissipation may vary with the turbulent structure under consideration, the values of ε lying within a relative narrow range of 8×10^{-2} to $1.7 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-3}$.

KOLMOGOROV (1962) and OBUKHOV (1962) in independent studies conclude that the variation of the dissipation rate of turbulent energy should increase with decrease in the length scale. Though large scale turbulence is essentially anisotropic, OBUKHOV approximated the spectral (empirical energy distribution) by

$$E(k) = c\varepsilon^{2/3}k^{-5/3}, \quad (3)$$

where k , the wave number, is inversely proportional to l . According to OBUKHOV successive measurements in the atmosphere show that, although each measurement is in satisfactory agreement with a $-5/3$ exponent in a certain range of scales, the intensity of turbulence varies from measurement to measurement, which may be explained by variance of the energy dissipation rate ε . He considers that $\overline{\varepsilon}$ statistically is a constant and $\overline{\varepsilon}^{1/3}$ is proportional to l^α where $\overline{\varepsilon}$ is the mean value of successive measurements of ε and $1 \gg \alpha > 0$.

According to the theory by KRAICHNAN (1959), the energy spectrum follows the $-3/2$ exponent instead of the $-5/3$ exponent.

2. Empirical relation of the energy dissipation rate and the scale of turbulence

The rate of energy dissipation has been considered to be constant in the inertia subrange; but the value of each largest eddy in each sea with different sizes will change with the scale of the phenomena or the size of seas as follows.

One set of continuous current meter observations in Uruga Strait shows $\varepsilon \sim v^3/L = 2^3/239 = 3.3 \times 10^{-2} \text{ cm}^2 \text{ sec}^{-3}$ (NAN'NITI 1956), where the turbulent velocity v , that is $\langle v^2 \rangle^{1/2}$, is the r.m.s. turbulent velocity component associated with the largest eddy whose scale is L . Another set of current meter observations at the sea bottom of 600 m in Suruga Bay indicates $\varepsilon \sim U_*^3/\kappa_0 z = 0.7^3/(0.4 \times 10^2) = 8.9 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-3}$ and $L \sim v^3/\varepsilon = 3.4^3/(8.9 \times 10^{-3}) = 4.4 \times 10^3 \text{ cm}$ (NAN'NITI, 1962). By the increase in width of the envelope of the Kuroshio axis downstream, the size of the largest eddy is estimated to be 5×10^6 to 10^7 cm , $\langle v^2 \rangle^{1/2}$ is of the order of 10 to 20 cm sec^{-1} and the energy dissipation rate is the order of 10^{-4} to $1.6 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-3}$ (NAN'NITI, 1960). With the data of the floating pumices ejected from Myôjin Reef in 1952 (Oceanogr. Sec., CMO, 1952) the author estimated $\langle v^2 \rangle^{1/2}$ by $U \times \langle Y^2 \rangle^{1/2}/X = 35 \times 120/600 = 7 \text{ cm sec}^{-1}$ (NAN'NITI, 1964 a). Assuming the size of largest eddy to be of the order of 10^6 cm and 10^7 cm , the same order fluctuation in the magnitude as of the current axis, the energy dissipation rate is 3.4×10^{-4} to $3.4 \times 10^{-5} \text{ cm}^2 \text{ sec}^{-3}$. By statistical study of the Columbia River plume, the mean value of the largest eddy is $5 \times 10^6 \text{ cm}$ and the r.m.s. turbulent velocity is 5.4 cm sec^{-1} (NAN'NITI, 1964 b). So the energy dissipation rate is $3.1 \times 10^{-5} \text{ cm}^2 \text{ sec}^{-3}$.

With these estimations, a relationship is shown in Figure 1 in which the rate of energy dissipation ε and the size of largest eddies L are used as the coordinates. The figure shows that the energy dissipation rate is not a constant but changes as a negative power of the size of the largest eddies.

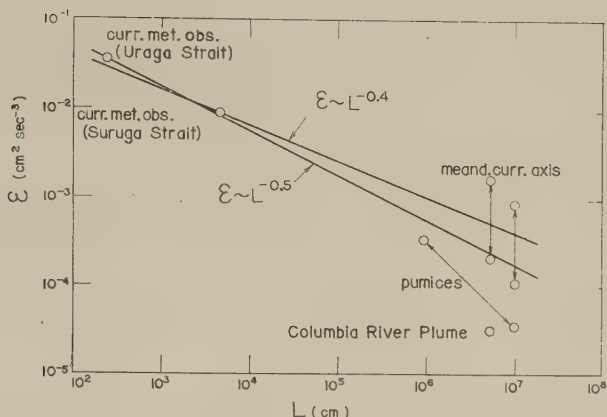


Fig. 1. Relationship between energy dissipation rate and scale of largest eddies.

We have the relation from Figure 1 as

$$\varepsilon \sim L^{-\alpha} \sim l^{-\alpha}, \quad (4)$$

where α is approximately 0.4 to 0.5 over the range 10^2 to 10^7 cm.

There is a large number of bays or seas with different sizes, and the large-scale diffusion experiments were made in the open sea and the small-scale experiments in embayments. The size of each observed largest eddy, L , is recognized as proportional to the size of the sea in which it was observed. This means also that for each observed largest eddy, the calculated energy dissipation rate, ε , these are the representative ones in the sea which the observation was done. Therefore we may say ε depends upon L , and as for the scale of phenomena, l , is proportional to the scale of largest eddy, L , we may say $\varepsilon \sim L^{-\alpha} \sim l^{-\alpha}$ just as the relationships $K \propto l^{4/3}$ (STOMMEL, 1949), or $K \propto l^{1.19}$ (OKUBO, 1962) have been deduced from experiments in a large number of seas with different sizes.

It is not clear which characteristic of them, the depth or the size of the seas, is more effective than the other to the dependency of ε upon L .

3. Turbulence theory without assumption of inertia subrange

The energy dissipation rate, ε , can be represented by

$$\varepsilon \sim v^2 / \tau, \quad (5)$$

where $\langle v^2 \rangle^{1/2}$ is the r.m.s. turbulent velocity component associated with the largest eddy and v^2 is the turbulent kinetic energy; τ is the lifetime of the largest eddy, or it is the dissipation time of the kinetic energy per unit mass. Assuming the relationship $\tau \sim L/v$ into the equation (5), then;

$$\varepsilon \sim v^3/L. \quad (6)$$

This relation should hold without the assumption of an inertia subrange.

Substituting equation (4) into (6), one finds the turbulent component of velocity, v , where

$$v \sim L^{(1-\alpha)/3}. \quad (7)$$

The diffusion coefficient K , may be assumed to be equal to the product of characteristic velocity and a characteristic length of eddy, thus we write

$$K \sim Lv \sim L^{(4-\alpha)/3}. \quad (8)$$

Putting $\alpha = (0.4+0.5)/2 = 0.45$ from Figure 1 into the above, the following relationship is obtained $K \sim L^{1.18} \sim l^{1.18}$.

OKUBO's empirical formula $K = 0.023 l_0^{1.19}$ (OKUBO, 1962), with K in $\text{cm}^2 \text{sec}^{-1}$ and l_0 in cm, holds in the range $10^3 \leq l_0 \leq 10^9$ cm. Putting $l_0 = 4L$ as he took $l_0 = 4\sigma_r$, the above formula can be written as

$$K = 0.12 L^{1.19}. \quad (9)$$

Combining equations (8) and (9),

$$\alpha = 0.43. \quad (10)$$

This value, $\alpha = 0.43$, falls within the range $0.4 \leq \alpha \leq 0.5$ derived from Figure 1. So the new proposal, the dependency of ε upon L , is supported by OKUBO's empirical formula. It is important to note that all these equations hold without introducing the assumptions of an inertia subrange, or the similarity hypotheses of turbulence.

This dependency of the rate of energy dissipation of the largest eddies per unit mass and time upon the representative scale of phenomena or the size of seas coupled with the assumption of a steady state of turbulent energy flow against the scale suggest that some energy is supplied in all size scales of turbulence. Therefore, there may be many sinks or sources of energy for each scale of turbulence. If the assumption of the steady state is applied to the oceanic system as a whole, then the total amount of local energy supply should be equal to the total amount consumed for each scale of turbulence.

The r.m.s. turbulent velocity component, $\langle v^2 \rangle^{1/2}$, is proportional to

$$\langle v^2 \rangle^{1/2} \sim L^{(1-\alpha)/3} \sim L^{0.19} \sim l^{0.19} \quad (11)$$

by equations (7) and (10).

The lifetime, τ , can be written as

$$\tau \sim v^2/\varepsilon \sim L^{0.81} \sim l^{0.81} \quad (12)$$

by equations (4), (5), (10) and (11).

How long does the largest eddy last? The time change of the vorticity at

the center of the Rankine's vortex with the radius r_0 in an isolated state is given (McEWEN, 1948).

$$\zeta = \zeta_0 \{1 - \exp(-r_0^2/4Kt)\}. \quad (13)$$

For $t=30$ days and $r_0=50$ km ($L=2r_0=100$ km) the ratio ζ/ζ_0 becomes 0.1 for $K=2.3 \times 10^7$ cm² sec⁻¹ (ICHIYE, 1956). The lifetime is proportional to the period in which its vorticity becomes zero. So if we define the lifetime, τ , by $\zeta/\zeta_0=0.1$ when $t=\tau$, then the equation (13) becomes

$$r_0^2/K\tau \doteq 0.4. \quad (14)$$

This result is implied by (9) and (12). Putting the equation (9) and the relation $L=2r_0$ into equation (14), yields equation (12) in the form:

$$\tau = 5.2 l^{0.81}. \quad (15)$$

Numerical results of diffusion coefficient and lifetime of the largest eddy in each sea with different sizes by equations (9) and (15) are tabulated in Table 1.

Table 1. Estimated diffusion coefficient and lifetime as functions of the scale of turbulence

l (cm)	10^3	10^4	10^5	10^6	10^7	10^8	10^9
K (cm ² sec ⁻¹)	4.4×10^2	6.9×10^3	1.1×10^5	1.7×10^6	2.6×10^7	4.0×10^8	6.2×10^9
τ (sec)	1.4×10^3	9.0×10^3	5.8×10^4	4.2×10^5	2.7×10^6	1.8×10^7	1.1×10^8

As shown in Table 1, the author expects many eddies of various scales and various lifetimes, which govern the oceanic conditions each having definite diffusion coefficients. The oceanic phenomena can be explained as the results of turbulences in relation to the scale, the lifetime, and the diffusion coefficient. The time scale of oceanic variations may be considered as either the lifetime or the passage time of largest eddies. The scale of phenomena is proportional to TU and also we have the following relation as $L \sim \tau v$, so the scale of phenomena can be written as

$$L \sim l \sim TU \sim \tau v, \quad (16)$$

where T is the passage time and U is the mean velocity.

If an observer keeps his position fixed in space, he will observe a period of a passage time T as an Eulerian correlation which becomes zero, and if he moves with a water, he will observe a lifetime τ by a Lagrangian method. The ordinary value of v/U is the order of 0.1 to 1. So the lifetime is usually ten times or less longer than the passage time. We must pay attention to the manner in which the observations were made for the periods of oceanic changes correspond to the lifetime or to the passage time as observed.

4. *Observed oceanic phenomena*

MIYAKE and SARUHASHI (1958) obtained $K = (1.0, 1.4) \times 10^9 \text{ cm}^2 \text{ sec}^{-1}$ empirically from the time change of the distribution of the radioactivity diffused out from the source after 270 and 420 days. HIDAHA (1950) adopted $K = 1.89 \times 10^9 \text{ cm}^2 \text{ sec}^{-1}$ and MIYAZAKI (1952) adopted $K = 1.38 \times 10^9 \text{ cm}^2 \text{ sec}^{-1}$ as the coefficient of eddy viscosity, which is much the same as the diffusion coefficient, for the theoretical consideration of the general circulation of the Pacific Ocean. From these results the present author expects the largest eddies to have a lifetime of the order of a year and a scale of length of a few thousands kilometers (Table 1).

The numerical values of diffusion coefficients computed by the downstream spreading-out of the envelope of monthly or seasonal observations of current axes, the climatological-mean values, are $K = (1.8 \text{ and } 2.8) \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$ in the Gulf Stream (STOMMEL, 1951) and $(1.3 \text{ to } 2.1) \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$ in the Kuroshio (NAN'NITI, 1960).

STOMMEL (1955) suspected his value as being high and questioned the real cross-stream transport owing to the filament-like distribution of low salinity water by FORD, LONGARD and BANKS (1952), along the Gulf Stream for at least 1200 miles. This is an indication that small-scale turbulent processes tending to transfer properties across the stream in the upper layer are inconsiderable (STOMMEL, 1958). STOMMEL (1955) on analyzing a set of current observations in the Florida Straits, found that the coefficient of eddy viscosity was less than $10^6 \text{ cm}^2 \text{ sec}^{-1}$ so he doubted the reality of his former high value. The present author thinks that STOMMEL's (1955) value should be smaller than expected for the scale of variations, $7 \times 10^7 \text{ cm}$, which flowed past the point of observation during the week of observation, because the station was too near the coast to permit the large eddies to fully develop; also considers the wavy meander-like structures of stream produce a net cross-stream transport as their positions have no correlation with each other (NAN'NITI, 1960).

MIYAZAKI (1952) found that an inshore counter-current near the western edge of the ocean can be obtained formally by letting the coefficient decrease toward the coast, which corresponds to $2.16 \times 10^7 \text{ cm}^2 \text{ sec}^{-1}$ in the coastal region and $1.38 \times 10^9 \text{ cm}^2 \text{ sec}^{-1}$ farther off shore, which appears to be a reasonable assumption. Furthermore the viscosity coefficient of general circulation or the climatological mean flow pattern of the Pacific Ocean probably should be taken as having a magnitude of $10^9 \text{ cm}^2 \text{ sec}^{-1}$, though MUNK and CARRIER took 5×10^7 and $10^8 \text{ cm}^2 \text{ sec}^{-1}$ (MUNK and CARRIER, 1950). The scale of phenomenon, as $K = 10^9 \text{ cm}^2 \text{ sec}^{-1}$,

is 2.2×10^8 cm and the lifetime is 11.5 months.

HIDAKA (1950) adopted $K=1.89 \times 10^9$ cm² sec⁻¹ to obtain the westward intensification of current and MUNK and CARRIER (1950) took $K=5 \times 10^7$, 10^8 cm² sec⁻¹ to compare the width of ocean currents at some instant, but their stationary theory should be compared with the more wider climatological mean width. The equation (9) and some observed facts (MIYAKE and SARUHASHI, 1958) show that the diffusion coefficient of the climatological mean flow pattern of the Pacific Ocean should be taken $K=10^9$ cm² sec⁻¹.

Strictly speaking, the empirically deduced equation (9) should be applied to phenomena of relative diffusion from a floating source only. But one may intuitively assume that the above equation can be applied to the relation between scale and eddy viscosity coefficient of continuous fixed source type; in other words, the scale of turbulence pertinent to the problem of the general circulation may be just the same order of the scale of floating source phenomena analyzed by MIYAKE and SARUHASHI, so their eddy viscosity and diffusion coefficients should be 10^9 cm² sec⁻¹.

The diffusion coefficients of the order of 5×10^7 , 10^8 cm² sec⁻¹ are related to the ordinary eddies in the subarctic convergence regions as shown in the former computation by the current axis fluctuations, further in the following sentences.

Operation Cabot observed many cyclonic eddies whose scale are of the order of 2×10^7 cm. (FUGLISTER and WORTHINGTON, 1951). The shifting of the Gulf Stream position by as much as 11 miles per day suggests the passage time of largest eddy is $T \sim L/U = 2 \times 10^7 / 23 \div 10^6$ sec = two weeks or less.

VON ARX, BUMPUS and RICHARDSON reported the shingle structure of the Gulf Stream and suggested that its structure is related to a day's discharge of water from the Gulf of Mexico by a diurnal tide. (VON ARX, BUMPUS and RICHARDSON, 1955). The scale of eddies is estimated at $L \sim TU = 1.3 \times 10^7$ to 2.6×10^7 cm, as the passage time of eddy should be one day (8.6×10^4 sec) and the mean velocity is $U = 150$ to 300 cm sec⁻¹.

This is the same order of the scale observed by Operation Cabot. The passage time will change from 10^6 sec to 8.6×10^4 sec as the mean current velocity changes to be 23 or 233 cm sec⁻¹. The passage time is the period in which an Eulerian correlation is reduced to zero. However their lifetime has a definite value on the order of a few months, and their diffusion coefficient is the order of 10^7 cm² sec⁻¹ (Table 1).

In 1954, a large anticyclonic eddy whose scale is about 3×10^7 cm was observed

off Honshu, Japan (MASUZAWA, 1957), which persisted in the entire year. It stayed nearly at the same place and was supplied energy from the Kuroshio, so it was not in an isolated state. It appears that the lifetimes of the isolated eddies whose scale is order of 10^7 cm, are usually a few months or less, for after two or three months, they may or may not be found.

The theoretical values for $r_0=5\times 10^6$ cm ($L=10^7$ cm), the diffusion coefficient, K , is 2.6×10^7 cm² sec⁻¹ and the lifetime, τ , is 2.7×10^6 sec=31 days from Table 1. These theoretical values are of the same order as ICHIYE's $K=2.3\times 10^7$ cm² sec⁻¹ and $\tau=30$ days (ICHIYE, 1956).

The vorticity calculated by dynamical computation is the magnitude of the order of 10^{-4} sec⁻¹ and its time variation is of the order of 10^{-11} sec⁻² (NAN'NITI, 1959). So the time, Δt , needed to consume its vorticity is roughly given by

$$\Delta t = \zeta / (\partial \zeta / \partial t), \quad (17)$$

which is of the order of 10^7 sec=3.8 months. In any case the lifetime of isolated eddy of this scale is the order of a few months.

As mentioned above, the most common scale of largest eddies observed in the Kuroshio and the Gulf Stream convergence regions is a few hundred kilometers. This value was obtained in the instantaneous stream taking the mean wave lengths of sinuous iso-thermal or iso-haline lines as 240 miles (480 km) and diffusion coefficients of $(2.8 \text{ and } 5.6)\times 10^7$ cm² sec⁻¹ from the rate of change of the gradient of chlorinity with distance (NAN'NITI, 1951). This wave length suggests that the scale of eddies is of the order of 2×10^7 cm, half of the wave length, and then by equation (9) $K=5.8\times 10^7$ cm² sec⁻¹. As the climatological-mean Kuroshio Stream, it showed a longer wave, about 1000 km, (NAN'NITI, 1960). This suggests that the scale of climatological-mean eddies is of the order of 5×10^7 cm and the diffusion coefficient is of the order of 1.7×10^8 cm² sec⁻¹. Thus the diffusion coefficient of the order of 5×10^7 , 10^8 cm² sec⁻¹ adopted to the general circulation by MUNK is related to the ordinary eddies in the subarctic convergence regions, but is too small in scale to apply to the general circulation of the ocean. Meanders in the stream depend heavily upon the existence of large-scale turbulence. Thus, as we have seen, individual eddies and meanders were statistically averaged out as turbulence.

Small-size eddies were reported by the five days interval observation (MASUZAWA, 1958), the present author estimates their scale as $L=5\times 10^6$ cm from MASUZAWA's Figure 2, this implied that $\tau=1.4\times 10^6$ days, $K=1.1\times 10^7$ cm² sec⁻¹ by equations (9) and (15). These eddies were reported to move at 50 cm sec⁻¹, giving a passage

time of $10^5 \text{ sec} \div 1.2 \text{ days} = \tau/14$. Accordingly it is reasonable that the observers sometimes found and sometimes missed them by observations spaced at five days intervals. An eddy of the same order was reported in the Columbia River plume (NAN'NITI, 1964 b). It had a mean observed turbulent component of velocity, $\langle v^2 \rangle^{1/2}$, of 5.4 cm sec^{-1} , a lifetime, τ , of $0.85 \times 10^6 \text{ sec}$ and a diffusion coefficient, K , of $1.6 \times 10^7 \text{ cm}^2 \text{ sec}^{-1}$, which were calculated by INOUE's method (INOUE, 1950) and they are reasonable values from Table 1.

A shorter period fluctuation was shown in MASUZAWA's Figure 3 (MASUZAWA, 1958), the present author estimates the order of the passage time as 10^h , and the mean flow velocity 0.5 kt . Then the scale of eddies become $9 \times 10^5 \text{ cm}$. This implies $K = 1.5 \times 10^6 \text{ cm}^2 \text{ sec}^{-1}$, $\tau = 3.4 \times 10^5 \text{ sec} = 3.9 \text{ days}$, nevertheless MASUZAWA obtained $K = 9 \times 10^6 \text{ cm}^2 \text{ sec}^{-1}$ by shearing stress.

The present author believes that there is no need to refer to eddies smaller than the above examples as there are so many papers concerning them.

5. Conclusion

The energy dissipation rate of the largest eddy in each sea with different sizes changes as a negative power of the size of eddies or seas.

The equations of turbulent factors deduced from the empirically deduced laws $K = 0.12 l^{1.19}$ and $\varepsilon \sim l^{-0.43}$ give the numerical results of the lifetime and the diffusion coefficient in terms of the scale of the eddies, and these equations hold without introducing the assumptions of an inertia subrange.

Observed oceanic phenomena such as the large scale circulation of the Pacific Ocean, the fluctuations of the current axes, or the meander, of the Kuroshio or the Gulf Stream and some kinds of eddies of different size accompanying them are explained as the result of turbulence of differing scales. They give diffusion coefficients agreeing well with those previously obtained.

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Theoretical Studies on Tidal Waves Travelling over the Rotating Globe (II)

By

Takeo UENO

Japan Meteorological Agency

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Contents

1. Introduction
2. The hydrodynamical equations for tides
3. The potential of tide generating force
4. The fundamental equations for M_2 tide
5. The fundamental equations for O_1 tide
6. Outline of computations

Abstract: In the preceding paper¹⁾ the author explained the fundamental equations for tidal waves caused by the moon's attraction and showed the results of M_2 tide in the Atlantic Ocean comparing with the observations at the isolated islands. In this paper the computed results at several stations in the Pacific and Indian Ocean, the distribution of sea-level, current, maximum amplitude and its phase lag-all over the lattices are shown. By this computation the existences of very large amphidromies and nodal lines are proved in the Pacific Ocean.

6. *Outline of computations (continue)*

In all the following figures the epoch is at the moon's upper culmination at Greenwich. Fig. 7, a, b and c show the variation of computed sea-level for M_2 tide at the representative stations in the Pacific and Indian Ocean. As to the tidal current, for which very few observations have been made in the deep sea, however, the writer gave only one example in Fig. 8⁶⁾. Fig. 9, a, b, c and d show the distribution of every three hours computed sea-level and current covering all the world. Fig. 10, a and b are the essence of this computation, where the maximum amplitude above mean sea-level and its occurrence for the M_2 tide all over the meshes are shown. In Fig. 10, a, we find the several points marked

with circles, where the value is very small. They are, called "amphidromy" also marked in Fig. 10, b, where the occurrences are rotating around them. Above all, we can see two of very large amphidromy and a train of them, a nodal line in the Pacific. The numerals in Fig. 10, a, b, in parenthesis are observed value. As known from Fig. 11~12, the co-tidal map by M. ROLLIN-A. HARRIS⁵⁾ and G. DIETRICH⁴⁾ respectively, in Fig. 10, b, the mesh is too rough to draw the co-tidal line near the coastal line, which is very different according to each author's image. Indeed, in Fig. 10, b, the rotating tidal waves around the amphidromies near the central part of Pacific are very like that in Fig. 11~12, however, it is very strange as shown in Fig. 9, a~d that the tidal currents should show the movement on lines all over the meshes.

The station name for station number in Fig. 3 of part I¹⁾ is as follows:

The station table.

No.	Name	No.	Name	No.	Name	No.	Name	No.	Name
1	Chili	11	Townsville	21	Norfolk	31	C. Hope	41	Coron
2	Peru	12	Hobert	22	S. P. 1	32	Mackenzie	42	C. Verde
3	Panama	13	Ross	23	S. P. 2	33	Indian	43	Fernando Is.
4	St. Barbara	14	Palao	24	C. Leeuwin	34	Chagos	44	Ascension Is.
5	Duch Harbar	15	Saipan	25	P. Darwin	35	Cocos	45	St. Helena
6	Kamchatka	16	Wake I.	26	Andaman Is.	36	New Amsterdam	46	Trinidad
7	Japan	17	Honolulu	27	Calcuta	37	Iceland	47	Montevideo
8	Hongkong	18	Fuji I.	28	Colombo	38	Azores	48	Tristan
9	Borneo	19	Tahiti I.	29	Karachi	39	Bermuda	49	C. Horn
10	Arafura	20	Eeater I.	30	Comoro Is.	40	Mexico	50	Weddell

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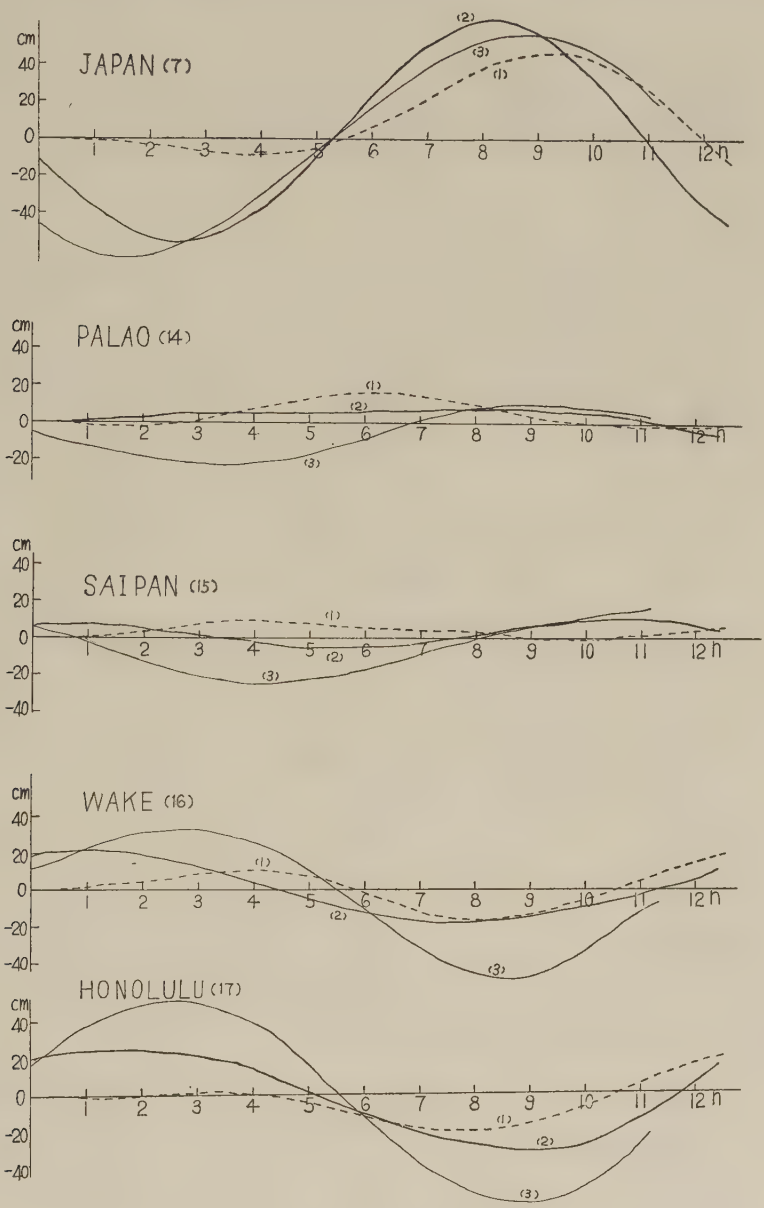


Fig. 7. (a). The variation of M_2 elevation. Numeral on each curve means the period of computation. Station number corresponds to Fig. 3 and station table (Epoch: upper culmination at Greenwich)

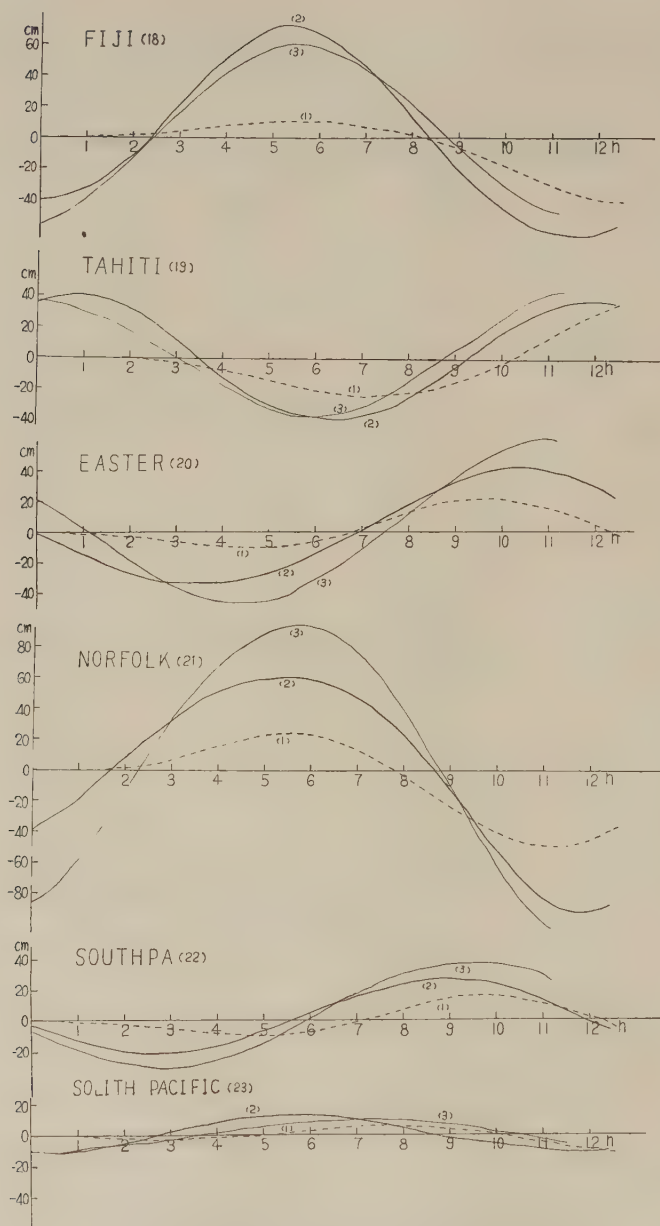


Fig. 7. (b). See the explanation for Fig. 7 (a).

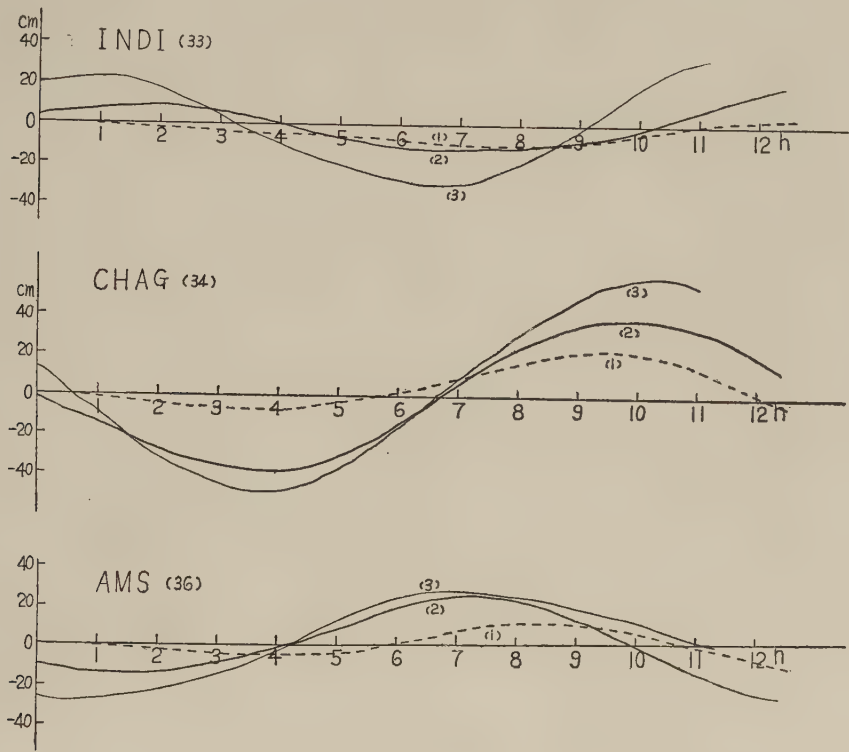


Fig. 7 (c). See the explanation for Fig. 7 (a).

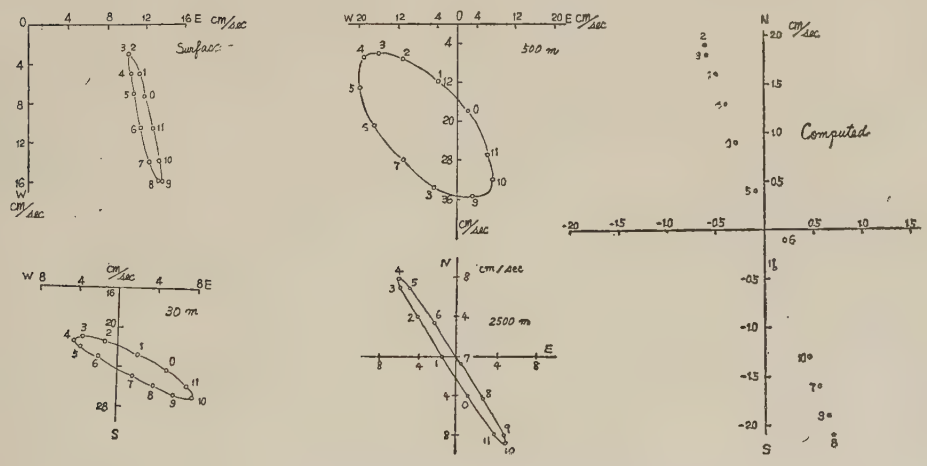


Fig. 8. Computed and observed current at $28^{\circ}7'5''$ S, $19^{\circ}20'8''$ W, Depth 4420 m, *Meteor*, Aug. 13~15, 1925. (Epoch: upper culmination at Greenwich)

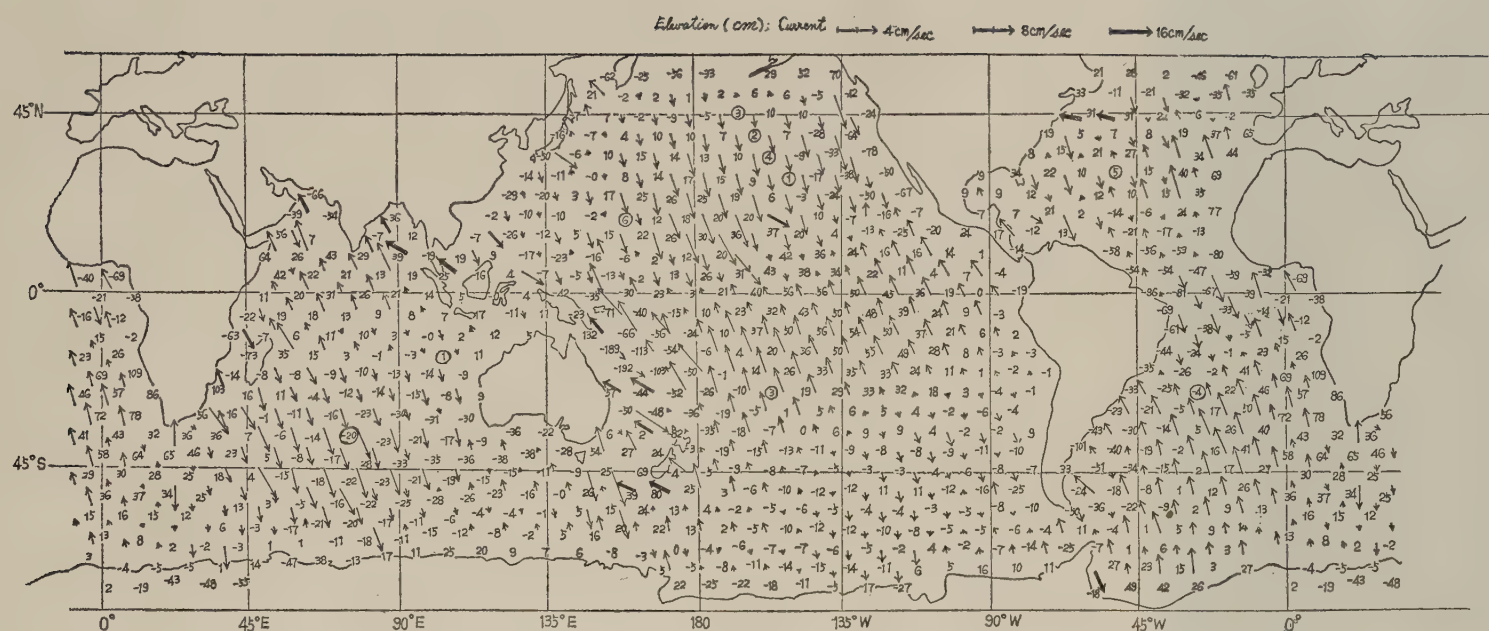


Fig. 9 (a). Elevation and current distribution for M_2 at 0 hr. (Epoch: upper culmination at Greenwich)

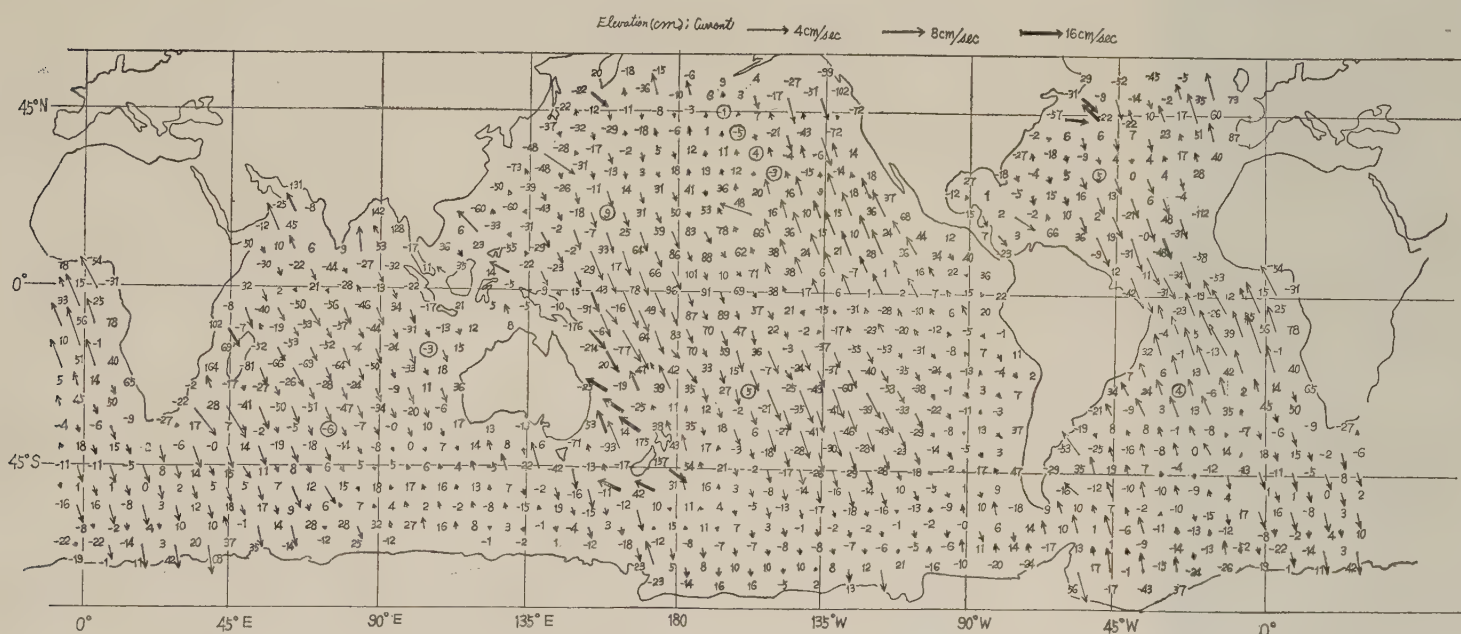


Fig. 9 (b). At 3 hr. See Fig. 9 (a).

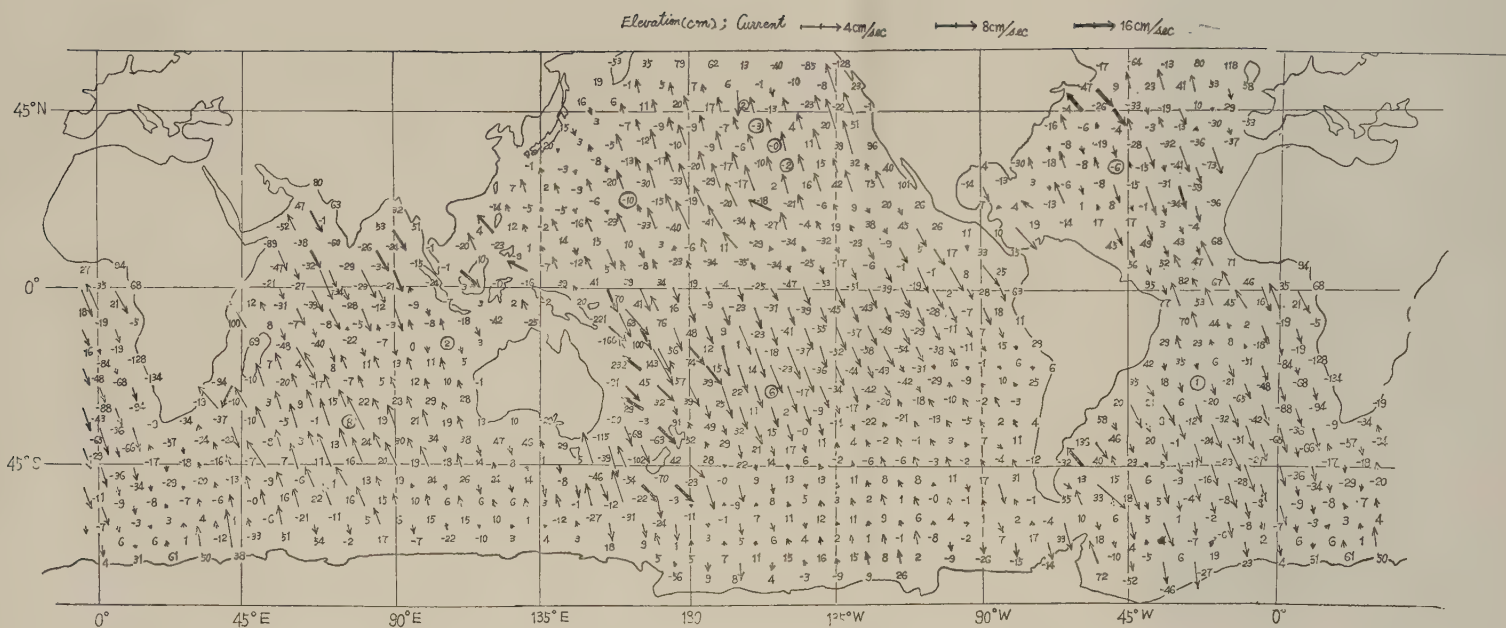


Fig. 9 (c). At 6 hr. See Fig. 9 (a).

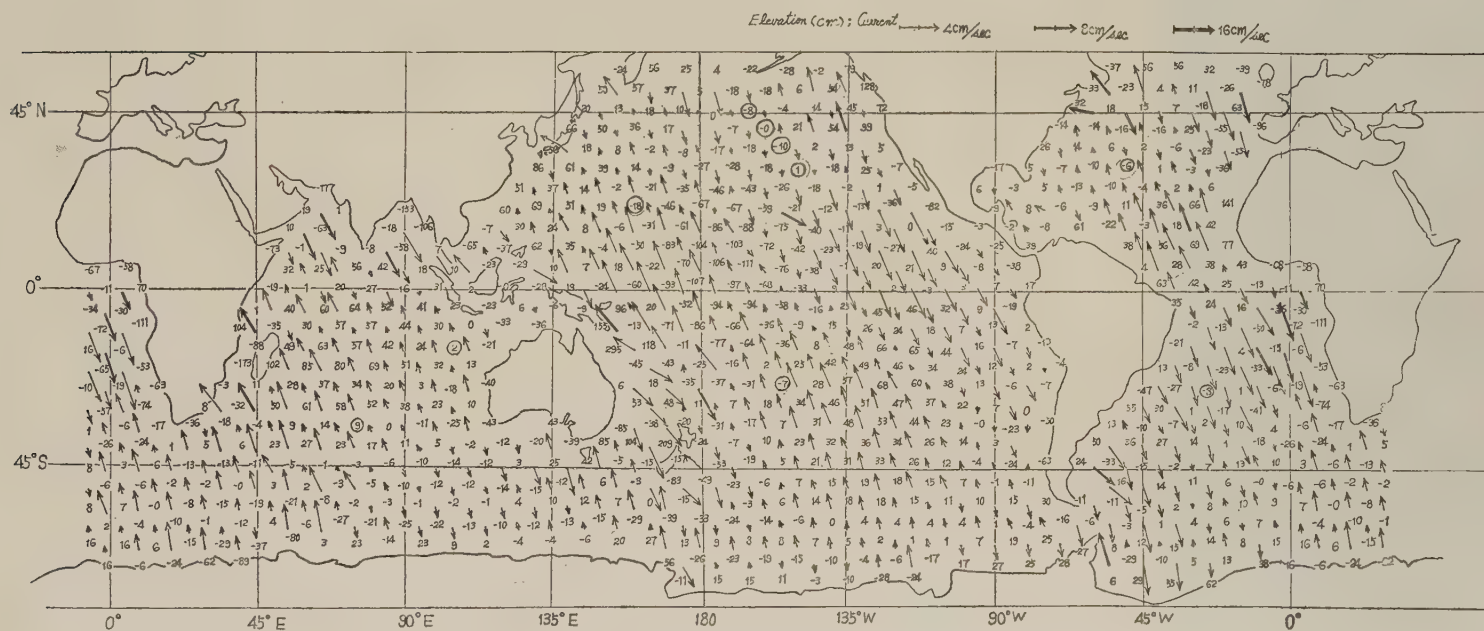


Fig. 9 (d). At 9 hr. See Fig. 9 (a).

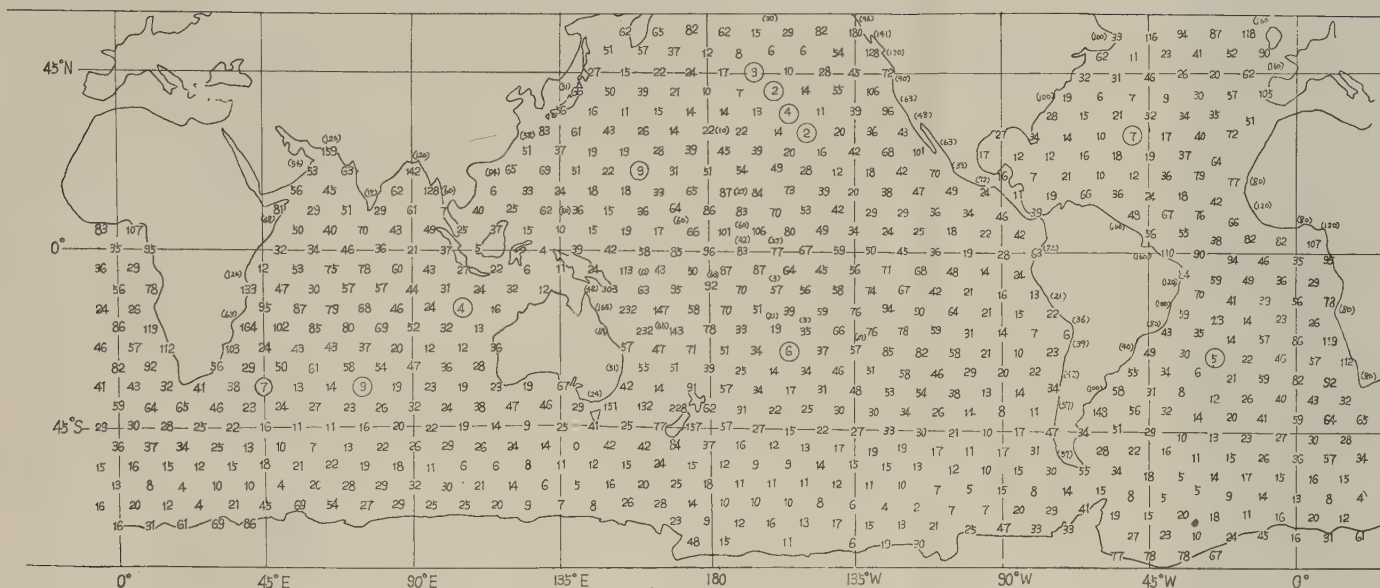


Fig. 10 (a). Distribution of maximum amplitude for M_2 tide.

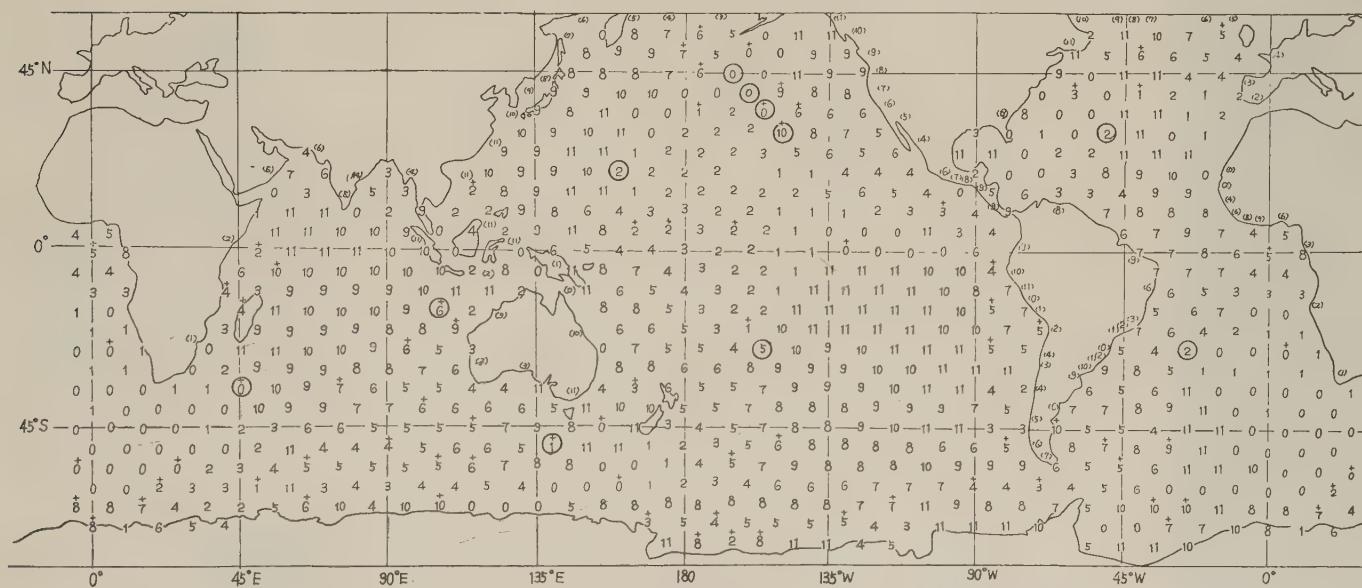


Fig. 10 (b). Occurrence of maximum amplitude in Fig. 10 (a). (Epoch: upper culmination at Greenwich)

Non-Linear Numerical Studies on Tides and Surges in the Central Part of Seto Inland Sea

By

Takeo UENO

Japan Meteorological Agency

(Received Dec. 18, 1964)

Abstract: Astronomical Tides, Storm Surges caused by the six typhoons were computed on the Central Part of Seto Inland Sea, where on the rotating sheet the hydro-dynamical equations with the non-linear terms, that is, N-S equations with whole the terms were numerically solved. In the case of surges the tidal interaction term was included. The prediction equation (*Sec. 5.2*), the method of differentiation for non-linear term (*Sec. 5.3*) and the arrangement of lattices (*Sec. 5.6*) were newly devised. The main data used in this computation are: Mesh interval $\Delta S=8$ km, time step $\Delta t=100$ sec. (both cases measured from current to current point or step). The wind stress law $\tau_s=\gamma^2 W|W|$, W is wind velocity, $\gamma^2=2.6\times 10^{-8}$. Bottom stress $\tau_b=\gamma^2 U|U|-0.25\tau_s$, U is mean current velocity. Horizontal mixing coefficient $L=1.3=10^6$. Pressure gradient and wind speed at every grid point were obtained every ten minutes from typhoon's every hour position and empirical pressure distribution law.

Contents

- Chapter 1. Introduction
- Chapter 2. The equation of motion and continuity
- Chapter 3. The fundamental equations with mass transport
- Chapter 4. The meteorological condition
- Chapter 5. The formulation of prediction equations
- Chapter 6. Results

Chapter 1. Introduction

The Seto Inland Sea, noted for the beautiful scenery of islands and peninsulas, many hot-springs and historic interests, also much attracts many people who belong to various special fields. We first notice its unique topography (Fig. 1), that is, a long inland sea extending east and west direction, surrounded by

Chugoku, Shikoku and Kyushu mountains. It is 440 km long from Osaka Bay to Suho Sea and only 4 km wide at Akashi, Kurushima and 8 km at Bisan Straits which divide this sea into main four parts, Osaka Bay, Harima Sea, Hiuchi Sea and the Western Part of Inland Sea. In the field of tides and surges we also find many characteristic phenomena of this sea, and on the Bay of Osaka and the Western Part they have already been made clear^{1), 2)}. The remaining part including Harima and Hiuchi Sea which is called the Central Part of Seto Inland Sea presents the most interesting but quite difficult problems to us. As to the topographic features, this sea is connected with the external seas through the several straits, that is, on the eastern boundary Akashi, Naruto and the western boundary Mihara, Hakuho and Kurushima Straits. Further this area is separated into two parts by Bisan straits including many small islands, peninsulas and channels. In addition to such the complicated features, at the spring high water the sea level reaches nearly 200 cm and the tidal current velocity shows 500 cm/sec, which sometimes give us records of extremely peculiar storm surges.

From these circumstances as mentioned above, on the Central Part of Seto Inland Sea the author is demanded to make clear the hydraulic phenomena of tides and surges, especially the interaction between the two using the hydrodynamical equations without neglecting the non-linear term for the high speed and irregular distribution of current, this is the first difficulty in this computation. The adopted mesh interval is 4 km from current to elevation point, though insufficient to represent such the irregular coastal lines, being restricted by the capacity of our computer IBM 704, this is the second difficulty. Our sea is a very long and narrow basin surrounded by three mountains as described above, so the wind accompanying with typhoons pass through here is inclined to have a special direction and too complicated to be presented with a simple formula used in the case of other seas, this is the third difficulty.

This paper is only a extract from Technical Report of the Japan Meteorological Agency No. 36 "Numerical Investigations of Storm surges in the Central Part of Inland Sea"³⁾, where theoretical considerations, programming for numerical computations, many figures of weather, tide and surge records and enormous tables of observed and computed data are edited. The results shown in this paper are astronomical tides (*Sec. 6.1*) and weather, surges caused by the five typhoons (*Sec. 6.2, 6.3*). Above all, in the case of "Toya-maru Typhoon", which in 1954 capsized the Aomori-Hakodate ferryboat (4337 tons) and caused the huge damages along the coast of Inland Sea, the comparisons between the observed

and computed weather surge results at all the tidal stations are shown in detail (Sec. 6.4).

Chapter 2. The equation of motion and continuity

To the fluid in the rotating sheet or rect-angular basin (Fig. 2), the following equation of motion applies;

$$\frac{D\mathbf{V}}{Dt} + 2\boldsymbol{\omega} \times \mathbf{V} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) = \mathbf{K} - \frac{1}{\rho\omega} \text{grad } P^* + \frac{1}{3} \nu^* \text{grad div } \mathbf{V} + \nu^* \Delta \mathbf{V},^{(4)} \quad (2.1)$$

where the origin of system 0 and the axes x, y are in the undisturbed surface and the axis z vertical and downwards. Further the symbols are defined as follows:

$\mathbf{V} (u, v, w)$; the velocity vector of fluid at any point A.

$\boldsymbol{\omega} (o, o, \omega)$; the rotational vector of system.

$\mathbf{r} (x, y, z)$; the vector showing the position A.

$\mathbf{K} (o, o, g)$; the external body force acting
a unit mass of fluid, g means the gravity.

P^* ; the total pressure at A.

$\rho\omega$; the density of fluid.

ν^* ; the coefficient of eddy viscosity.

Notice that in our system as shown in Fig. 2 the x, y axes are put to be clockwise at convenience of formation in vector for equation of motion so the component of $\boldsymbol{\omega}$ in the equation (2.1) is negative on the north hemisphere. Now we make the following considerations for the equation (2.1).

2.1. Incompressibility

Our fluid is, of course, hardly compressible. So the equation (2.1) is divided into two parts;

$$\frac{D\mathbf{V}}{Dt} + 2\boldsymbol{\omega} \times \mathbf{V} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) = \mathbf{K} - \frac{1}{\rho\omega} \text{grad } P^* + \nu^* \Delta \mathbf{V}, \quad (2.2)$$

$$\text{div } \mathbf{V} = 0. \quad (2.3)$$

2.2. Non-linear term

On the left side of (2.2) we have the next expression,

$$\frac{D\mathbf{V}}{Dt} = \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \text{ grad } \mathbf{V}. \quad (2.4)$$

The second term on the right side of (2.4), called the non-linear, field acceleration

or inertia term, is often neglected because of its small quantity or difficulty of method for treatment. This term, however, plays the important roles when the fluid velocity is large and its distribution is irregular such as in this case. For example, the table 1 shows the values of $\partial V/\partial t$ and $V \text{ grad } V$ at various points obtained from the tidal current in this computations.

Table 1. The value of $\partial V/\partial t$ and $V \text{ grad } V$.
[Computed when the max. time of grad V , multiplied by 10^3]

Station	Kurushima	Bisan	Akashi	Harima
grid (I, J)	10.48	11.19	10.6	8.12
$\partial V/\partial t$	8.0	2.0	4.4	2.3
$V \text{ grad } V$	28.0	2.5	5.0	0.4

From the above table we know that near the straights $V \text{ grad } V$ is larger than or comparable with $\partial V/\partial t$ and that near the center of bay the former is less than the latter by one order, which gives validity of our previous linear computations.

Analytical solutions of non-linear equation for water waves have been obtained in several cases. In the text book of H. LAMB⁵⁾ we can see the following simple example; No frictional and one dimensional movement equation for progressive waves in the long tidal river with constant depth h and width is

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial y} = -g \frac{\partial \zeta}{\partial y}, \quad (2.5)$$

which is obtained from the later equation (2.14), putting $\omega=0$, $v^*=0$ and $P=0$. On the other hand the continuity equation is

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial}{\partial y} \{ (h+\zeta)v \}$$

or

$$\frac{\partial \zeta}{\partial t} + v \frac{\partial \zeta}{\partial y} = -(h+\zeta) \frac{\partial v}{\partial y}. \quad (2.6)$$

The boundary condition at the mouth is

$$\zeta = a \cos \sigma t \quad \text{for } y=0. \quad (2.7)$$

The solution for (2.5), (2.6) and (2.7) is obtained by the successive approximation, that is,

$$\left. \begin{aligned} v &= \frac{ga}{c} \cos \sigma \left(t - \frac{y}{c} \right) - \frac{1}{8} \frac{g^2 a^2}{c^3} \cos 2\sigma \left(t - \frac{y}{c} \right) - \frac{3}{4} \frac{g^2 \partial a^2}{c^4} y \sin 2\sigma \left(t - \frac{y}{c} \right), \\ \zeta &= a \cos \sigma \left(t - \frac{y}{c} \right) - \frac{3}{4} \frac{g \partial a^2}{c^3} y \sin 2\sigma \left(t - \frac{y}{c} \right), \end{aligned} \right\} \quad (2.8)$$

where $c=\sqrt{gh}$. In the above equations the secondary waves with the angular velocity twice as large as that of original waves, make the flood current flat, the ebb current sharp, the elevation rise rapid and the elevation fall slow (Fig. 3, 4, 5). If we apply the above results to our model where $h=3\times 10^8$ (cm), $a=1.5\times 10^2$ (cm) [the amplitude of M_2 and S_2 tide at Hashihama (Fig. 9, 10)], $\sigma=1.4\times 10^{-4}$ (radian/sec) [the angular velocity of M_2 tide], the ratio of amplitude of secondary wave for v to that of primary is 0.006 and for ζ it becomes 0.1 near the center of our area $y=10^7$ (cm). In the real case the tidal wave in our area is not progressive, but stationary one as stated in (Sec. 6.1).

H. KREISS⁶⁾ analytically studies the non-linear oscillations in the uniformly wide and deep but various long tidal channels with the frictional term, where he cleared the variations of ebb and flood current according to the length and depth of channel. In the next paper the author shows the non-linear computation for the strait with the varying depth and width, which is connecting the two-tidal seas.

The above considerations shows in our model $\mathbf{V} \text{ grad } \mathbf{V}$ is the important term which cannot be neglected and (2.2) takes the following form,

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \text{ grad } \mathbf{V} + 2\boldsymbol{\omega} \times \mathbf{V} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) = \mathbf{K} - \frac{1}{\rho_\omega} \text{grad } P^* + \nu^* \Delta \mathbf{V}. \quad (2.9)$$

2.3. The total pressure gradient

In the equilibrium state under only the gravity (2.9) becomes

$$\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) = \mathbf{K} - \frac{1}{\rho_\omega} \text{grad } P^* \quad (2.10)$$

and the profile of free surface $z=-z_0$ is

$$z_0 = \frac{\omega^2}{2g} (x^2 + y^2).^{7)} \quad (2.11)$$

Next, the z component of (2.9) is

$$\frac{1}{\rho_\omega} \frac{\partial P^*}{\partial z} = g \quad (2.12)$$

because $w = \partial \zeta / \partial t \approx \zeta / \Delta t$, $\zeta = 1.5 \times 10^2$, $\Delta t = 10^2$ so Dw/Dt , $\nu^* \Delta w \ll g$.

Integrating (2.12) from $z=z$ to the disturbed surface $z=-(z_0+\zeta)$ where the atmospheric pressure P is acting, we get

$$\frac{1}{\rho_\omega} (P^* - P) = g(z + z_0 + \zeta)$$

or from (2.11)

$$\frac{P^*}{\rho_\omega} = \frac{P}{\rho_\omega} + g(z + \zeta) + \frac{\omega^2}{2}(x^2 + y^2).^{8)} \quad (2.13)$$

Thus, the component equation of motion (2.9) is

$$\left. \begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} &= 2\omega v - \frac{1}{\rho_\omega} \frac{\partial P}{\partial x} - g \frac{\partial \zeta}{\partial x} + \nu^* \Delta u, \\ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} &= -2\omega u - \frac{1}{\rho_\omega} \frac{\partial P}{\partial y} - g \frac{\partial \zeta}{\partial y} + \nu^* \Delta v. \end{aligned} \right\} \quad (2.14)$$

2.4. The atmospheric pressure gradient

The Atmospheric pressure is assumed to be expressed in the form (4.1). Then

$$\left. \begin{aligned} \frac{\partial P}{\partial x} &= \frac{a}{r_0^2} T_x, \\ \frac{\partial P}{\partial y} &= \frac{a}{r_0^2} T_y, \end{aligned} \right\} \quad (2.15)$$

where

$$\left. \begin{aligned} T_x &= [1 + (r/r_0)^2]^{-3/2} x, \\ T_y &= [1 + (r/r_0)^2]^{-3/2} y. \end{aligned} \right\} \quad (2.16)$$

2.5. The effect of Coriolis term

The latitude for the center of our model area is $34^\circ 20'N$, so the value of coriolis parameter f is

$$f = 2\omega = -0.8226 \times 10^{-4} \text{ (radian} \cdot \text{sec}^{-1}\text{)}. \quad (2.17)$$

as to negative sign, cf. explanation for (Sec. 2.1).

In the area illustrated by Fig. 2, the profile of surface elevation for the free wave progressing in the direction y is

$$\zeta = A \exp \{fx / \sqrt{gh}\} \cos \{k(ct - y) + \varepsilon\}.^{9)} \quad (2.18)$$

If we apply (2.18) to our model, where $h = 2 \times 10^3$ (cm), $x = 4 \times 10^6$ (cm),

$$\exp \{fx / \sqrt{gh}\} = 0.792.$$

That is, the amplitude of left hand side toward the progressing direction of wave is reduced to about 79% of right hand side.

2.6. The eddy viscosity

Our depth is very shallow compared with the horizontal dimension. That is, in the following expression

$$\nu^* \Delta u = \nu^* \frac{\partial^2 u}{\partial z^2} + \nu^* \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right),$$

the first term is related to the phenomena with the scale of 10^3 (cm) order and the others to those of 10^5 (cm) order, which is the grid interval. Those two are quite different phenomena and we must take the adequate value for ν^* according to the scale of phenomena. Now we suppose ν^* to be homogenous with the horizontal plane. Let ν and L be vertical and horizontal component of ν^* respectively, then the terms of eddy viscosity take the following formula

$$\left. \begin{aligned} \nu^* \Delta u &= \nu \frac{\partial^2 u}{\partial z^2} + L \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \\ \nu^* \Delta v &= \nu \frac{\partial^2 v}{\partial z^2} + L \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right). \end{aligned} \right\} \quad (2.19)$$

2.7. The equation of motion and continuity

The considerations mentioned above lead the final forms of equation of motion and continuity as follows;

$$\left. \begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} &= f v - g \frac{\partial \zeta}{\partial x} - \frac{a}{\rho_\omega r_0^2} T_x + \nu \frac{\partial^2 u}{\partial z^2} + L \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \\ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} &= -f u - g \frac{\partial \zeta}{\partial y} - \frac{a}{\rho_\omega r_0^2} T_y + \nu \frac{\partial^2 v}{\partial z^2} + L \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right), \end{aligned} \right\} \quad (2.20)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \quad (2.21)$$

2.8. The initial, boundary and mouth condition

Our fluid is assumed to be perfect viscous liquid that is, along the coast and bottom

$$u = v = 0. \quad (2.22)$$

The initial condition for surge computations is the astronomical tides (elevation and current at every mesh point) corresponding to the initial time, which is obtained from the computation for tides. The initial condition for tidal computations is, of course, $u = v = 0$, $\zeta = 0$ for all the mesh points.

The mouth condition is given at the east end, Akashi, and the west end, Hashihama. In the tidal computations they are the sea level variations corresponding to the $M_2 + S_2$ tide which form the simple harmonic vibrations with $12^h 25^m$ period. These oscillations at the mouths cause the inner fluid to move and after three periods the movement of fluid reaches the steady state which is not so differ from the state after the second period (Fig. 13). In the

surge computations, the mouth conditions are the sea level variations which consist of the observed surge (deviation from the astronomical tide) and the astronomical sea level corresponding to the typhoon's duration.

Chapter 3. The fundamental equations with mass transport

We cannot use the equations (2.20), (2.21) themselves as the prediction equations for tides or surges because of lacking in enough knowledge about the vertical structure of fluid movement, especially in the transient state under the wind action. Now we use, instead of u , v , the mass transport M , N defined by

$$\left. \begin{aligned} M &= \int_{-\zeta}^h u dz = (h + \zeta)U, \\ N &= \int_{-\zeta}^h v dz = (h + \zeta)V, \end{aligned} \right\} \quad (3.1)$$

where U , V the mean velocity with the vertical section. Then from (2.21) we can easily obtain the simple prediction equation with M , N for ζ which is one of the mostly desired. On the other hand, to re-write the equation (2.20) with M , N is very difficult. After the very excellent studies P. WELANDER⁽¹⁰⁾ and G. W. PLATZMAN⁽¹¹⁾ have recently leaded the prediction equation for mass transport. The author tried to integrate the equation (2.20) vertically term by term estimating their order as follows:

$$\left. \begin{aligned} \frac{\partial F}{\partial x} &\approx \frac{F}{\Delta s}, \quad \frac{\partial^2 F}{\partial x^2} \approx \frac{F}{(\Delta s)^2}, \quad \frac{\partial F}{\partial z} \approx \frac{F}{h}, \quad \frac{\partial F}{\partial t} \approx \frac{F}{\Delta t}, \\ \Delta s &= 8 \times 10^5 \text{ (cm)}, \quad \Delta t = 10^2 \text{ (sec)}, \\ U &= 10^2 \text{ (cm/sec)}, \quad \zeta = 10^2 \text{ (cm)}, \quad h = 3 \times 10^3 \text{ (cm)}. \end{aligned} \right\} \quad (3.2)$$

3.1. Integrating the left side of (2.20)

Now we consider the following integrals:

$$\left. \begin{aligned} I_x &= \int_{-\zeta}^h \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) dz, \\ I_y &= \int_{-\zeta}^h \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) dz. \end{aligned} \right\} \quad (3.3)$$

First, from the next differential form

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial t} \int_{-\zeta}^h u dz = \int_{-\zeta}^h \frac{\partial u}{\partial t} dz + u_s \frac{\partial \zeta}{\partial t},$$

we get the integral for the first term of I_x

$$\int_{-\zeta}^h \frac{\partial u}{\partial t} dz = \frac{\partial M}{\partial t} - u_s \frac{\partial \zeta}{\partial t}. \quad (3.4)$$

On the other hand the integral for the last term of I_x is, using the continuity equation,

$$\int_{-\zeta}^h w \frac{\partial u}{\partial z} dz = -w_s u_s + \int_{-\zeta}^h u \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dz.$$

If we apply the equation (3.23) to above equation, we get the expression for I_x . The same way can be applied to I_y and their forms are

$$\left. \begin{aligned} I_x &= \frac{\partial M}{\partial t} + u_s \left(u_s \frac{\partial \zeta}{\partial x} + v_s \frac{\partial \zeta}{\partial y} \right) + \int_{-\zeta}^h \left(\frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} \right) dz, \\ I_y &= \frac{\partial N}{\partial t} + v_s \left(u_s \frac{\partial \zeta}{\partial x} + v_s \frac{\partial \zeta}{\partial y} \right) + \int_{-\zeta}^h \left(\frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} \right) dz. \end{aligned} \right\} \quad (3.5)$$

Now we compare each term in I_x , I_y with the first term. First

$$u_s^2 \frac{\partial \zeta}{\partial x} / \frac{\partial M}{\partial t} \approx \frac{\zeta}{h} U \frac{\Delta t}{\Delta s} \ll U \frac{\Delta t}{\Delta s}.$$

Next, if we put

$$\begin{aligned} U &= U + u' \quad u' \ll U, \\ \int_{-\zeta}^h \frac{\partial u^2}{\partial x} dz / \frac{\partial M}{\partial t} &\approx \left(U + 2u' + \frac{u'^2}{U} \right) \frac{\Delta t}{\Delta s}. \end{aligned}$$

Retaining the leading terms in (3.5) from the comparisons above mentioned, we get the integrals as follows:

$$\left. \begin{aligned} I_x &= \int_{-\zeta}^h \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) dz = \frac{\partial M}{\partial t} + (h + \zeta) E_x, \\ I_y &= \int_{-\zeta}^h \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) dz = \frac{\partial N}{\partial t} + (h + \zeta) E_y, \end{aligned} \right\} \quad (3.6)$$

where

$$E_x = \frac{\partial U^2}{\partial x} + \frac{\partial UV}{\partial y}, \quad E_y = \frac{\partial UV}{\partial x} + \frac{\partial U^2}{\partial y}. \quad (3.7)$$

3.2. The wind and bottom stress

The problems on laws of wind and bottom stress are the most difficult ones in the surge computations as well as the weather conditions. They finally reduce to the vertical structure of flow and will not perfectly solved without aid of both the turbulent theory and the observations of wind and current at marine towers. On the other hand the author believe it is another matter to re-examine these problems after leading the prediction equation without neglecting any term. Then the writer used in this paper the laws of wind and bottom stress which have been adopted since our preceding investigations. Our brief idea for this matter is as follows:

a) The wind stress

In the next integrals for the vertical viscosity terms in (2.20)

$$\left. \begin{aligned} \int_{-\zeta}^h \nu \frac{\partial^2 u}{\partial z^2} dz &= \nu \frac{\partial u}{\partial z} \Big|_{z=h} - \nu \frac{\partial u}{\partial z} \Big|_{z=-\zeta}, \\ \int_{-\zeta}^h \nu \frac{\partial^2 v}{\partial z^2} dz &= \nu \frac{\partial v}{\partial z} \Big|_{z=h} - \nu \frac{\partial v}{\partial z} \Big|_{z=-\zeta}, \end{aligned} \right\} \quad (3.8)$$

we put the second terms on the right to the following symbols:

$$\begin{aligned} \nu \frac{\partial u}{\partial z} \Big|_{z=-\zeta} &= -\frac{1}{\rho_w} \tau_s^x, \\ \nu \frac{\partial v}{\partial z} \Big|_{z=-\zeta} &= -\frac{1}{\rho_w} \tau_s^y. \end{aligned}$$

According to our definition the left side express the stress of unit mass on the positive side (water mass) acting on the negative side (atmosphere) through the unit area of boundary. Then τ_s^x , τ_s^y mean the component of wind stress acting on the water through unit surface. For the expression of wind stress we adopt the following formula:

$$\left. \begin{aligned} \tau_s^x &= \rho_a \gamma_s^2 R = \rho_a \gamma_s^2 W_x \sqrt{W_x^2 + W_y^2}, \\ \tau_s^y &= \rho_a \gamma_s^2 S = \rho_a \gamma_s^2 W_y \sqrt{W_x^2 + W_y^2}, \\ \tau_s^2 &= 2.6 \times 10^{-3}, \quad \rho_a = 1.2 \times 10^{-3}. \end{aligned} \right\} \quad (3.9)$$

The wind stress law, above all, the value of γ_s^2 mentioned above has been examined by not only observations at the open sea where the surface slope is balanced with the long lasted wind, but analytical discussions based on the experiment in laboratory. It is very interesting that many of studies on wind action deduce the same formula (3.9) which is now used quite often in the numerical prediction for surges and as far as we notice the maximum surges when the state is nearly steady one, the computed value is generally in good agreement with the observation.

b) The bottom stress

Now we put the first terms on the right side of (3.8) to the next form

$$\begin{aligned} \nu \frac{\partial u}{\partial z} \Big|_{z=h} &= \frac{1}{\rho_w} \tau_b^x, \\ \nu \frac{\partial v}{\partial z} \Big|_{z=h} &= \frac{1}{\rho_w} \tau_b^y, \end{aligned}$$

which express the stress of positive side (the bottom) acting on the unit mass on the negative side (water mass) through the unit area of boundary. The law of bottom stress is more complicated than the wind stress law and the various expressions have been deduced or used in both analytical studied and numerical

computations. In the tidal current, where the velocity distribution is nearly uniform from surface to bottom and near the bottom the velocity rapidly reduces to zero, the following frictional law analogous to the wind stress law (3.9) has been often used:

$$\left. \begin{aligned} \tau_b^x &= -\rho_w \gamma_b^2 U \sqrt{U^2 + V^2}, \\ \tau_b^y &= -\rho_w \gamma_b^2 V \sqrt{U^2 + V^2}, \\ \gamma_b^2 &= 2.6 \times 10^{-3}, \quad \rho_w = 1. \end{aligned} \right\} \quad (3.10)$$

In the presence of wind stress, H. YAMADA¹²⁾, providing in the $x-z$ plane that

$$\begin{aligned} u &= u_0 + u_1 z + u_2 z^2, \\ -\nu \frac{\partial u}{\partial z} &= \frac{1}{\rho_w} \tau_s^x \quad \text{for } z=0, \\ u &= 0 \quad \text{for } z=h, \end{aligned}$$

deduced the next formula

$$\tau_b^w = -\rho_w \frac{3\nu}{h} U + \frac{1}{2} \tau_s^x. \quad (3.11)$$

The above, however, can be re-written to

$$\left. \begin{aligned} \tau_b^x &= -\rho_w \gamma_b^2 U |U| + \frac{1}{2} \tau_s^x, \\ \tau_b^y &= \frac{3\nu}{h} |U|, \\ \nu &= \frac{\gamma_b^2}{3} h |U|. \end{aligned} \right\} \quad (3.12)$$

If we take the value (3.10) for γ_b^2 , we get the value of ν from (3.12). For example, in the case of numerical computations for storm surges in Osaka Bay, where $h=27$ m, $U=70$ cm/sec, it becomes $\nu=182$ C. G. S. which is almost equal to the value 160 which is obtained from the decay of seiches by M. MIYAZAKI¹³⁾.

On the other hand R. O. REID¹⁴⁾, providing in the $x-z$ plane that

$$\left. \begin{aligned} \tau^x(z) &= \tau_b^x + (\tau_s^x - \tau_b^x) \frac{z}{h}, \\ \tau^x(z) &= L^2 \left| \frac{du}{dz} \right| \frac{du}{dz}, \\ L &= \frac{k_0}{h} (z + z_1)(h - z + z_0), \end{aligned} \right\} \quad (3.13)$$

where k_0 : Kármán constant=0.4,

z_0 : roughness for bottom $\ll h$,

z_1 : roughness for the surface $\approx \frac{h}{3000}$,

concluded that

$$\left. \begin{aligned} \tau_b^x &= -\rho_w \gamma_b^2 U |U| + 5 \gamma_b \tau_s^x \quad \text{for } W < 5.6U, \\ \tau_b^x &= -\rho_w \gamma_b^2 U |U| \quad \text{for } \tau_s^x = 0, \\ \gamma_b^2 &= 0.214 \left(\frac{z_0}{h} \right)^{1/6}. \end{aligned} \right\} \quad (3.14)$$

In the above formula, if we put $h=30$ m, $z_0=2$ cm, we obtain that

$$\gamma_b^2 = 2.6 \times 10^{-3}, \quad 5\gamma_b = 0.25.$$

From the considerations mentioned above, we may put the general expression for bottom stress to the next form:

$$\left. \begin{aligned} \tau_b^x &= -\rho_w \gamma_b^2 U \sqrt{U^2 + V^2} + k \tau_s^x, \\ \tau_b^y &= -\rho_w \gamma_b^2 V \sqrt{U^2 + V^2} + k \tau_s^y, \\ \gamma_b^2 &= 2.6 \times 10^{-3}. \end{aligned} \right\} \quad (3.15)$$

Where k should be decided in the numerical experiment, and we take the value 0.25.

Combining (3.9) and (3.15), we get the integrals for (3.8) as follows:

$$\left. \begin{aligned} \int_{-\zeta}^h \nu \frac{\partial^2 u}{\partial z^2} &= (1+k) \frac{\rho_a \gamma^2}{\rho_w} R - \gamma^2 \frac{Q}{(h+\xi)^2} M, \\ \int_{-\zeta}^h \nu \frac{\partial^2 v}{\partial z^2} &= (1+k) \frac{\rho_a \gamma^2}{\rho_w} S - \gamma^2 \frac{Q}{(h+\xi)^2} N, \end{aligned} \right\} \quad (3.16)$$

$$\left. \begin{aligned} R &= W_x |W|, \quad S = W_y |W|, \quad Q = \sqrt{M^2 + N^2}, \\ \gamma^2 &= 2.6 \times 10^{-3}, \quad k = 0.25. \end{aligned} \right\} \quad (3.17)$$

3.3. The horizontal mixing

For the value of horizontal eddy viscosity L which appears in the last term on the right side of (2.20), the author adopted the following idea: According to the turbulent theory L is proportional to the 4/3th power of scale of phenomena, the interval of most neighbouring current point $\Delta s'$ (Fig. 8). On the other hand, in the Kuroshio current, the ocean current running off the south of the Japanese coast, it is said from the observation that L has the value $10^6 \sim 10^7$. As the computation for that area has been made with the 15 km mesh interval²⁾, we may take the next expression for L

$$L = 2 \times 10^{-2} [\Delta s']^{4/3}, \quad \Delta s' = \Delta s / \sqrt{2}. \quad (3.18)$$

In our case $\Delta s = 8 \times 10^5$ cm, then

$$L = 1.3 \times 10^6. \quad (3.19)$$

Now we compare in (2.20) the horizontal mixing term with the vertical one. From (3.18), (3.12) and (3.2)

$$L \frac{\partial^2 u}{\partial x^2} / \nu \frac{\partial^2 u}{\partial z^2} = \frac{10h}{[4s]^{2/3}} \frac{1}{U} \approx 10^{-2}. \quad (3.20)$$

Then in the integrals $\int_{-\zeta}^h L \frac{\partial^2 u}{\partial z^2} dz$ etc., we can neglect such the small quantities as in (3.5) and get next integrals

$$\left. \begin{aligned} \int_{-\zeta}^h L \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) dz &= L \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} \right), \\ \int_{-\zeta}^h L \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) dz &= L \left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2} \right). \end{aligned} \right\} \quad (3.21)$$

Further for the small continuity of (3.21) as seen in (3.20), we may separately treat this term from the others, that is, we made every a few steps, not each step, the numerical computations for the following diffusion equation caused by the horizontal mixing;

$$\left. \begin{aligned} \frac{\partial M}{\partial t} &= L \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} \right) = L A_1 M, \\ \frac{\partial N}{\partial t} &= L \left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2} \right) = L A_1 N, \\ A_1 &= \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}, \quad L = 1.3 \times 10^2. \end{aligned} \right\} \quad (3.22)$$

According to (3.18) (3.22), and (5.20), the half life time for M, N is related to $4s$, and in our case it is about 12 hours.

3.4. The integral for continuity equation

Let consider the integral of (2.21) with respect to z from h to $-\zeta$.

First
$$\int_{-\zeta}^h \frac{\partial w}{\partial z} dz = -w_s.$$

On the other hand, from the expression for free surface F and its total derivation

$$\begin{aligned} F(x, y, z, t) &= \zeta(x, y, t) + z = 0, \\ \frac{DF}{Dt} &= \frac{\partial \zeta}{\partial t} + u_s \frac{\partial \zeta}{\partial x} + v_s \frac{\partial \zeta}{\partial y} + w_s = 0, \end{aligned} \quad (3.23)$$

we obtain the following formula;

$$\int_{-\zeta}^h \frac{\partial w}{\partial z} dz = \frac{\partial \zeta}{\partial t} + u_s \frac{\partial \zeta}{\partial x} + v_s \frac{\partial \zeta}{\partial y}.$$

While in the same way for (3.4)

$$\int_{-\zeta}^h \frac{\partial u}{\partial x} dz = \frac{\partial M}{\partial x} - u_s \frac{\partial \zeta}{\partial x}, \quad \int_{-\zeta}^h \frac{\partial v}{\partial y} dz = \frac{\partial N}{\partial y} - v_s \frac{\partial \zeta}{\partial y}.$$

Then the integral for equation of continuity is

$$\int_{-\zeta}^h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) dz = \frac{\partial \zeta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0. \quad (3.24)$$

3.5. The fundamental equations with mass transport

Consequently by the integral with respect to z from $-\zeta$ to h , (2.20) and (2.21) are transformed to the equations with mass transport. Their forms are, if a showed in mb, from (3.6), (3.16), (3.21) and (3.24),

$$\left. \begin{aligned} \frac{\partial M}{\partial t} &= fN - g(h+\zeta) \frac{\partial \zeta}{\partial x} - \gamma^2 \frac{Q}{(h+\zeta)^2} M - (h+\zeta) E_x - \frac{10^3 a}{\rho_w r_0^2} (h+\zeta) T_x \\ &\quad + \frac{1+k}{\rho_w} \rho_a \gamma^2 R + L A_1 M, \\ \frac{\partial N}{\partial t} &= -fM - g(h+\zeta) \frac{\partial \zeta}{\partial y} - \gamma^2 \frac{Q}{(h+\zeta)^2} N - (h+\zeta) E_y - \frac{10^3 a}{\rho_w r_0^2} (h+\zeta) T_y \\ &\quad + \frac{1+k}{\rho_w} \rho_a \gamma^2 S + L A_1 N, \end{aligned} \right\} \quad (3.25)$$

$$\frac{\partial \zeta}{\partial t} = - \left(\frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} \right). \quad (3.26)$$

The boundary conditions along the coast is, from (2.22)

$$M = N = 0. \quad (3.27)$$

Chapter 4. The meteorological conditions

The method for this problem is quite the same as we have used in the preceding investigations^{1), 2)} as mentioned below.

4.1. The computed typhoons

The typical typhoons which have passed through the Central Part of Inland Sea and caused much damages along the coast are the next five ones.

1. Ruth 17 hr. 14th—11 hr. 15th, Sept. 1951.
2. 5421 12 hr. 13rd—12 hr. 14th, Sept. 1954.
3. Toya 1 hr. 26th—13 hr. 26th, Sept. 1954.
4. 6016 10 hr. 29th— 4 hr. 30th, Aug. 1960.
5. 2nd Muroto 3 hr. 16th—21 hr. 16th, Sept. 1960.

Their pathes and every hour position are shown in Fig. 1 and Fig. 6. The weather observations over the sea in the typhoon area have hardly made, so in the storm surge computations we necessary provide the weather elements at all

the mesh points. This problem may be solved after the structure of typhoon is perfectly solved, which is usually done by analysis after the typhoon's passage. While we are urgently asked for predicting the surges. For this purpose, beside the studies on the structure of typhoon, to forecast the surges using the supposed parameters according to the typhoon such as the path, depression at center and radius of violent area is for the present, very important matter.

4.2. The distribution of atmospheric pressure

The author adopted the next FUJITA's formula¹⁵⁾ which expresses the distribution of atmospheric pressure in the area under the typhoon

$$p = p_{\infty} - a(t) \sqrt{1 + (r/r_0)^2}, \quad (4.1)$$

where

p : the air pressure on the sea surface at any point whose distance from the center is r .

p_{∞} : the air pressure in the area out of typhoon.

a : the pressure fall at the center of typhoon from p_{∞} .

r_0 : a unknown constant refering to the scale of typhoon.

Striktly speaking p_{∞} , a and r_0 are depend on time, but to decide such the functions with time is the same to predict the growth or decline of typhoon, that is, unpractical matter. So the author put only a to the function with time, which is observed every hour and is interpolated every ten minutes, while p_{∞} and r_0 are supposed to be constant during all the typhoon's passage except Ruth Typhoon which separated into three parts in its passage. We have decided these parameters about so many typhoons which attacked Japan and caused the huge surges, that it has become easy problem to seek for such constants of the

Table 2. The Constant for typhoon
[a : value at typhoon's most approachment]

Typh.	a (mb)	r_0 (km)	p_{∞} (mb)	C_1	C_2	Period
Ruth A	63	130	1013	4/7	0.6	17 hr.~23 hr.
Ruth B	47	160	1013	4/7	0.6	23 hr.~ 5 hr.
Ruth C	43	190	1013	4/7	0.6	5 hr.~11 hr.
5412	48	220	1013	4/7	0.6	all passage
Toya	40	105	1005	4/7	0.6	"
6016	25	45	997	6/7	0.6	"
2 Muroto	60	40	990	6/7	0.6	"

approaching typhoon and compute or forecast the surges which will happen during its passage.

Table 2 shows those parameters used in this computations.

4.3. The wind distribution

The wind distribution in the typhoon area is much complicated than that of pressure. As mentioned above, the author takes the following simple model for wind system: the wind velocity $\mathbf{W}$ is supposed to consist of two parts (Fig. 7), one is the field wind $\mathbf{F}$ whose direction coincides with that of typhoon's velocity $\mathbf{V}$ and the speed exponentially decrease according to the distance r from the center of typhoon. Another is the symmetric wind $\mathbf{G}$ which takes the direction inwards at an angle of 30° with the isobar and the speed is proportional to the gradient wind G_g deduced from the pressure distribution law (4.1). Then the components of field wind F_x, F_y are

$$\left. \begin{aligned} F_x &= C_1 V_x \exp(-\pi r/5 \times 10^7), \\ F_y &= C_1 V_y \exp(-\pi r/5 \times 10^7), \end{aligned} \right\} \quad (4.2)$$

where C_1 is a constant various with the typhoon as seen in Table 2. In our experience C_1 is $6/7$ for comparatively small value of r_0 and $4/7$ for large r_0 . The expression (4.2) says the value F at $r=500$ km is that of center multiplied by $e^{-\pi}$. On the other hand the gradient wind G_g is defined by the following equilibrium condition for the centrifugal force, the Coriolis force and the pressure gradient:

$$\rho_a \frac{G_g^2}{r} + \rho_a f_w G_g = \frac{dp}{dr}. \quad (4.3)$$

On the north hemisphere the wind in the typhoon is anti-clockwise and in (4.3), $f_w = 2\omega \sin \varphi$, where ω is positive. [Cf. Chapter 2, explanation for (2.1)]. Neglecting the second order, from (4.3) we obtain

$$G_g = \sqrt{\frac{r}{\rho_a} \frac{dp}{dr} - \frac{f_w}{2} r}.$$

Combining above formula with (4.1)

$$G_g = \sqrt{\frac{a'}{\rho_a} \frac{r}{r_0} Z^{3/2} - \frac{f_w}{2} r}, \quad (4.3)$$

where $a' = 10^3 a$. (a : mb).

Then the formula G_g with a (mb) becomes

$$\left. \begin{aligned} G_g &= \left[\sqrt{\frac{10^3}{\rho_a} \frac{1}{r_0} Z^{3/2} - \frac{f_w}{2} a^{-1/2}} \right] a^{1/2} r, \\ Z &= [1 + (r/r_0)]^{-1/2}. \end{aligned} \right\} \quad (4.4)$$

Consequently the components of symmetric wind G_x, G_y are

$$\left. \begin{aligned} G_x &= -\frac{C_2 G_0}{r} (0.500x - 0.866y), \\ G_y &= -\frac{C_2 G_0}{r} (0.866x + 0.500y), \end{aligned} \right\} \quad (4.5)$$

where the constant C_2 is 0.6 for all the typhoons as shown in Table 2.

The final expression for wind blowing over the sea under the sea under the typhoon is, from (4.2) and (4.5),

$$\left. \begin{aligned} W_x &= C_1 V_\infty \exp\left(-\frac{r\pi}{5.10^7}\right) - \left[C_2 \sqrt{\frac{10^3}{\rho a}} \frac{1}{r_0} Z^{3/2} - C_2 \frac{f_w}{2} a^{-1/2} \right] a^{1/2} \times (0.500x - 0.866y), \\ W_y &= C_1 V_\infty \exp\left(-\frac{r\pi}{5.10^7}\right) - \left[C_2 \sqrt{\frac{10^3}{\rho a}} \frac{1}{r_0} Z^{3/2} - C_2 \frac{f_w}{2} a^{-1/2} \right] a^{1/2} \times (0.866x + 0.500y). \end{aligned} \right\} \quad (4.6)$$

Chapter 5. The formulation of prediction equations

As illustrated in Fig. 9 an example for arrangement of mesh points, our mesh interval is $\frac{1}{2}\Delta x = \frac{1}{2}\Delta y = \frac{1}{2}\Delta S$ and time step interval $\frac{1}{2}\Delta t$. Now we define F the value of a function $F(x, y, t)$ at any mesh point $x = i \cdot \frac{1}{2}\Delta S$, $y = j \cdot \frac{1}{2}\Delta S$ and time $t = \tau \cdot \frac{1}{2}\Delta t$ ($i=0, 1, 2, \dots$; $j=0, 1, 2, \dots$; $\tau=0, 1, 2, \dots$), then the differential ratios are replaced by the central finite difference ratios as follows;

$$\left. \begin{aligned} \left(\frac{\partial F}{\partial x}\right)_{i,j}^\tau &\approx \left(\frac{\Delta F}{\Delta S}\right)_{i,j}^\tau = \frac{F_{i+1,j}^\tau - F_{i-1,j}^\tau}{\Delta S}, \\ \left(\frac{\partial F}{\partial t}\right)_{i,j}^\tau &\approx \left(\frac{\Delta F}{\Delta t}\right)_{i,j}^\tau = \frac{F_{i,j}^{\tau+1} - F_{i,j}^{\tau-1}}{\Delta t}, \\ \left(\frac{\partial^2 F}{\partial x^2} + \frac{\partial^2 F}{\partial y^2}\right)_{i,j}^\tau &\approx \frac{1}{\Delta S^2} [F_{i+2,j}^\tau + F_{i-2,j}^\tau + F_{i,j+2}^\tau + F_{i,j-2}^\tau - 4F_{i,j}^\tau]. \end{aligned} \right\} \quad (5.1)$$

Our final works are to bring the fundamental equations (3.25), (3.26) into the finite-difference forms, which become the prediction equations for elevation and current.

5.1. The difference form of equation of continuity

According to (5.1), (3.26) becomes at i, j

$$\zeta_{i,j}^{\tau+1} = \zeta_{i,j}^{\tau-1} - [M_{i+1,j}^\tau - M_{i-1,j}^\tau + N_{i,j+1}^\tau - N_{i,j-1}^\tau] \frac{\Delta t}{\Delta S},$$

or by using the next definitions

$$X_{i,j}^{\tau} = M_{i,j}^{\tau} \frac{dt}{ds}, \quad Y_{i,j}^{\tau} = N_{i,j}^{\tau} \frac{dt}{ds}, \quad (5.2)$$

$$\zeta_{i,j}^{\tau+1} = \zeta_{i,j}^{\tau-1} - [X_{i+1,j}^{\tau} - X_{i-1,j}^{\tau} + Y_{i,j+1}^{\tau} - Y_{i,j-1}^{\tau}]. \quad (5.3)$$

This is our prediction equation for the elevation of sea surface.

5.2. The formulation of difference equation of motion

In (3.25) we may compute the horizontal mixing terms independently from the others as mentioned in Sec. 3.3, further let x', y' to be the inhomogeneous terms with M, N , then we can re-write the fundamental equations for M, N , (3.25) as follows:

$$\left. \begin{aligned} \frac{\partial M}{\partial t} &= fN - \Gamma M + \varphi', \\ \frac{\partial N}{\partial t} &= -fM - \Gamma N + \psi', \end{aligned} \right\} \quad (5.4)$$

where

$$\Gamma = \gamma^2 \sqrt{M^2 + N^2} / (h + \zeta)^2, \quad (5.5)$$

and φ', ψ' consist of the sea-level gradient, non-linear, air-pressure gradient and wind stress terms as written in (3.25). In addition to (5.2) we use the following definitions:

$$\left. \begin{aligned} \varphi &= \varphi' \frac{dt}{ds}, \\ \psi &= \psi' \frac{dt}{ds}. \end{aligned} \right\} \quad (5.6)$$

Then the formula (5.4) become

$$\left. \begin{aligned} \frac{\partial X}{\partial t} &= fY - \Gamma X + \varphi, \\ \frac{\partial Y}{\partial t} &= -fX - \Gamma Y + \psi. \end{aligned} \right\} \quad (5.7)$$

If we re-write (5.7) in the central finite difference form at time $t = \tau + 1$, where we use the following assumption for X and Y on the right side of (5.7)

$$X^{\tau+1} = (X^{\tau+2} + X^{\tau})/2,$$

$$Y^{\tau+1} = (Y^{\tau+2} + Y^{\tau})/2,$$

then we obtain the next equations,

$$\begin{aligned} \frac{X^{\tau+2} - X^{\tau}}{2} &= f \frac{Y^{\tau+2} + Y^{\tau}}{2} - \Gamma \frac{X^{\tau+2} + X^{\tau}}{2} + \varphi^{\tau+1}, \\ \frac{Y^{\tau+2} - Y^{\tau}}{2} &= -f \frac{X^{\tau+2} + X^{\tau}}{2} - \Gamma \frac{Y^{\tau+2} + Y^{\tau}}{2} + \psi^{\tau+1}. \end{aligned}$$

Solve the above equations with respect to $(X, Y)^{\tau+2}$, we get the prediction equations for current,

$$\begin{aligned} \left\langle \frac{X}{Y} \right\rangle^{\tau+2} = & \left\{ \left[1 - \left(\frac{\Gamma \Delta t}{2} \right)^2 - \left(\frac{f \Delta t}{2} \right)^2 \right] \left\langle \frac{X}{Y} \right\rangle^{\tau} \pm f \Delta t \left\langle \frac{Y}{X} \right\rangle^{\tau} \right. \\ & - g(h + \zeta)^{\tau+1} \frac{(\Delta t)^2}{\Delta s} \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \left\langle \frac{\frac{\partial \zeta}{\partial x}}{\frac{\partial \zeta}{\partial y}} \right\rangle \pm \frac{f \Delta t}{2} \left\langle \frac{\frac{\partial \zeta}{\partial y}}{\frac{\partial \zeta}{\partial x}} \right\rangle \right]^{\tau+1}, \\ & - (h + \zeta)^{\tau+1} \frac{(\Delta t)^2}{\Delta s} \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \left\langle \frac{E_x}{E_y} \right\rangle \pm \frac{f \Delta t}{2} \left\langle \frac{E_y}{E_x} \right\rangle \right]^{\tau+1} \\ & - \frac{10^3 a}{\rho_w r_0^2} (h + \zeta)^{\tau+1} \frac{(\Delta t)^2}{\Delta s} \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \left\langle \frac{T_x}{T_y} \right\rangle \pm \frac{f \Delta t}{2} \left\langle \frac{T_y}{T_x} \right\rangle \right]^{\tau+1}, \\ & \left. + \frac{1+k}{\rho_w} \rho_a \gamma^2 \frac{(\Delta t)^2}{\Delta s} \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \left\langle \frac{R}{S} \right\rangle \pm \frac{f \Delta t}{2} \left\langle \frac{S}{R} \right\rangle \right]^{\tau+1} \right\} \\ & / \left[\left(1 + \frac{\Gamma \Delta t^2}{2} \right)^2 + \left(\frac{f \Delta t}{2} \right)^{\tau+1} \right]^{\tau+1}. \end{aligned} \quad (5.8)$$

Notice that the y component of elevation gradient, non-linear, pressure gradient and wind stress term appear in the expression for X through $f \Delta t / 2$, vice versa, which have the effect to strengthen the coriolis force. Then, related to the boundary condition (see *Sec. 5.6*), X and Y are so closely connected each other that there is no necessity for "smoothing". The prediction equations like (5.8) are also obtained by P. WELANDER¹⁰⁾ and G. W. PLATZMAN¹¹⁾.

5.3. The difference form of non-linear term

The arrangement of current points are illustrated in Fig. 8. Then, using the neighbouring four current points $(l \pm 1, m \pm 1)$, we can obtain at a mesh point (l, m) the finite difference form of E_x, E_y which are defined by (3.7). Take the new axis x' and y' making the angle 45° with the axis x and y . Let U', V' be the velocity component related to the new axis, then from the next relations

$$\left. \begin{aligned} U' &= (U + V) / \sqrt{2}, \quad V' = (-U + V) / \sqrt{2}, \\ \frac{\partial}{\partial x} &= \left(\frac{\partial}{\partial x'} - \frac{\partial}{\partial y'} \right) / \sqrt{2}, \quad \frac{\partial}{\partial y} = \left(\frac{\partial}{\partial x'} + \frac{\partial}{\partial y'} \right) / \sqrt{2}, \end{aligned} \right\} \quad (5.9)$$

E_x, E_y become

$$\left\langle \frac{E_x}{E_y} \right\rangle = \left[\left(\frac{\partial U'^2}{\partial x'} + \frac{\partial U'V'}{\partial y'} \right) \mp \left(\frac{\partial U'V'}{\partial x'} + \frac{\partial V'^2}{\partial y'} \right) \right] / \sqrt{2}. \quad (5.10)$$

The difference forms for (5.10) are, using the next symbols and definitions,

$$\left. \begin{aligned} UX_{l,m} &= 2U'_{l,m}(U'_{l+1,m+1} - U'_{l-1,m-1}), \\ VY_{l,m} &= 2V'_{l,m}(V'_{l-1,m+1} - V'_{l+1,m-1}), \\ UVX_{l,m} &= U'_{l,m}(V'_{l+1,m+1} - V'_{l-1,m-1}) + V'_{l,m}(U'_{l+1,m+1} - U'_{l-1,m-1}), \\ UVY_{l,m} &= U'_{l,m}(V'_{l-1,m+1} - V'_{l+1,m-1}) + V'_{l,m}(U'_{l-1,m+1} - U'_{l+1,m-1}), \\ \left\langle \frac{EX}{EY} \right\rangle_{l,m} &= (UX + UVY)_{l,m} \mp (UVX + VY)_{l,m}, \\ \frac{\partial}{\partial x'} &= \frac{\partial}{\partial y'} = 1 / \sqrt{2} \Delta s, \end{aligned} \right\} \quad (5.11)$$

$$\left\langle \frac{E_x}{E_y} \right\rangle_{l,m} = \frac{1}{2\Delta s} \left\langle \frac{EX}{EY} \right\rangle_{l,m}. \quad (5.12)$$

This scheme has the following four points of advantage.

- The truncation error. This error is proportional to the 3rd power of the mesh interval. Then, to compute the non-linear terms at the point (l, m) , if we use $(U, V)_{l \pm 2, m \pm 2}$, this truncation error will become $2^{3/2}$ times larger than that in our scheme where $(U, V)_{l \pm 1, m \pm 1}$ are used.
- The boundary. Along the boundary this scheme need not any additional mesh point which is never used to compute the other terms.
- The complicated topography. This scheme is valid for any canal curved with the sharp edge (Fig. 8), which we can see quite often in this computed area (Fig. 11).
- The conjugate lattices. According to the explanation in *Sec. 5.6* and illustration in Fig. 9, this scheme strengthens the connection between the two conjugate lattice series.

5.4. The difference form of equation of motion

Using (5.12) and the central difference form for $\frac{\partial \xi}{\partial x}$ and $\frac{\partial \xi}{\partial y}$, we obtain from (5.8) the predictions for X, Y .

$$\begin{aligned} \left\langle \frac{X}{Y} \right\rangle_{l,m}^{\tau+2} &= \left\{ \left[1 - \left(\frac{\Gamma \Delta t}{2} \right)^2 - \left(\frac{f \Delta t}{2} \right)^2 \right] \left\langle \frac{X}{Y} \right\rangle_{l,m}^{\tau} \pm f \Delta t \left\langle \frac{Y}{X} \right\rangle_{l,m}^{\tau} \right. \\ &\quad - g(h + \xi)_{l,m}^{\tau+1} \left(\frac{\Delta t}{\Delta s} \right)^2 \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \left\langle \frac{\xi}{\eta} \right\rangle_{l,m}^{\tau+1} \pm \frac{f \Delta t}{2} \left\langle \frac{\eta}{\xi} \right\rangle_{l,m}^{\tau+1} \right] \\ &\quad - \frac{1}{2} (h + \xi)_{l,m}^{\tau+1} \left(\frac{\Delta t}{\Delta s} \right)^2 \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \left\langle \frac{EX}{EY} \right\rangle_{l,m}^{\tau+1} \pm \frac{f \Delta t}{2} \left\langle \frac{EY}{EX} \right\rangle_{l,m}^{\tau+1} \right] \\ &\quad \left. - \frac{10^3 a}{\rho \omega r_0^2} (h + \xi)_{l,m}^{\tau+1} \frac{\Delta t^2}{\Delta s} \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \left\langle \frac{T_x}{T_y} \right\rangle_{l,m}^{\tau+1} \pm \frac{f \Delta t}{2} \left\langle \frac{T_y}{T_x} \right\rangle_{l,m}^{\tau+1} \right] + \right\} \end{aligned}$$

$$\begin{aligned}
 & + \frac{1+k}{\rho_w} \rho_a \gamma^2 \frac{(\Delta t)^2}{\Delta s} \left[\left(1 + \frac{\Gamma \Delta t}{2} \right) \langle R \rangle_{l,m}^{\tau+1} \pm \frac{f \Delta t}{2} \langle S \rangle_{l,m}^{\tau+1} \right] \Big\} \\
 & \quad / \left[\left(1 + \frac{\Gamma \Delta t}{2} \right)^2 + \left(\frac{f \Delta t}{2} \right)^2 \right]^{\tau+1}, \quad (5.13)
 \end{aligned}$$

where

$$\xi_{l,m}^{\tau+1} = \zeta_{l+1,m}^{\tau+1} - \zeta_{l-1,m}^{\tau+1}, \quad \eta_{l,m}^{\tau+1} = \zeta_{l,m+1}^{\tau+1} - \zeta_{l,m-1}^{\tau+1}, \quad \Gamma = \Gamma_{l,m}^{\tau+1}. \quad (5.14)$$

Now the time required for numerical computations is proportional to the number of terms computed every time step, in our computations only X , Y and ζ are computed every time step, others are put to be constant during a few step and computed every large step ΔT including several steps $n \cdot \Delta t$. This supposition may be true except the case the current velocity and its time variation is large. Then dropping the terms of the order $(f \Delta t)^2$, $(\Gamma \Delta t)^2$ and $f \Delta t \cdot \Gamma \Delta t$, the above equation (5.13) reduces to the following form:

$$\langle X \rangle_{l,m}^{\tau+2} = A_{l,m}^T X_{l,m}^{\tau} \pm f \Delta t \langle Y \rangle_{l,m}^{\tau} - B_{l,m}^T \left[\langle \xi \rangle_{l,m}^{\tau+1} \pm \frac{f \Delta t}{2} \langle \eta \rangle_{l,m}^{\tau+1} \right] + \langle \Psi \rangle_{l,m}^T, \quad (5.15)$$

where

$(\xi, \eta)_{l,m}^{\tau+1}$ are defined in (5.14),

$$\begin{aligned}
 \langle \Psi \rangle_{l,m}^T = & -\frac{1}{2g} B_{l,m}^T \left[\langle EX \rangle_{l,m}^T \pm \frac{f \Delta t}{2} \langle EY \rangle_{l,m}^T \right] \\
 & - \alpha_{l,m}^T \left[\langle T_x \rangle_{l,m}^T \pm \frac{f \Delta t}{2} \langle T_y \rangle_{l,m}^T \right] + \beta_{l,m}^T \left[\langle R \rangle_{l,m}^T \pm \frac{f \Delta t}{2} \langle S \rangle_{l,m}^T \right],
 \end{aligned}$$

$$A_{l,m}^T = 2/D_{l,m}^T - 1,$$

$$B_{l,m}^T = g(h + \zeta)_{l,m}^T \left(\frac{\Delta t}{\Delta s} \right)^2 / D_{l,m}^T,$$

$$\alpha_{l,m}^T = \frac{10^3 \bar{\alpha}}{\rho_w r_0^2} (h + \zeta)_{l,m}^T \frac{(\Delta t)^2}{\Delta s} / D_{l,m}^T,$$

$$\beta_{l,m}^T = \frac{1+k}{\rho_w} \rho_a \gamma^2 \frac{(\Delta t)^2}{\Delta s} / D_{l,m}^T,$$

$$D_{l,m}^T = 1 + \Gamma_{l,m}^T \Delta t / 2,$$

$$\Gamma_{l,m}^T = \gamma^2 \frac{\Delta s}{\Delta t} [\sqrt{X^2 + Y^2} / (h + \zeta)^2]_{l,m}^T,$$

$$(h + \zeta)_{l,m}^T = h_{l,m} + \frac{1}{4} [\zeta_{l+1,m-1}^T + \zeta_{l-1,m-1}^T + \zeta_{l-1,m+1}^T + \zeta_{l+1,m+1}^T],$$

$$(EX, EY)_{l,m}^T = \text{defined in (5.9) and (5.11)},$$

$$(T_x, T_y)_{l,m}^T = \text{defined in (2.16)},$$

$$(R, S)_{l,m}^T = \text{defined in (3.17), (4.6)}.$$

(5.16)

The current velocity is obtained, from the relations (3.1) and (5.2), as follows:

$$\left\langle \frac{U}{V} \right\rangle_{l,m}^T = -\frac{1}{(h+\zeta)_{l,m}^T} \frac{\Delta s}{\Delta t} \left\langle \frac{X}{Y} \right\rangle_{l,m}^T. \quad (5.17)$$

5.5. The difference form of horizontal mixing term

Our diffusion equation for X, Y caused by the horizontal maxing are from (3.22) and (5.2)

$$\left. \begin{aligned} \frac{\partial X}{\partial t} &= L \left(\frac{\partial^2 X}{\partial x^2} + \frac{\partial^2 Y}{\partial y^2} \right), \\ \frac{\partial Y}{\partial t} &= L \left(\frac{\partial^2 Y}{\partial x^2} + \frac{\partial^2 X}{\partial y^2} \right). \end{aligned} \right\} \quad (5.18)$$

As mentioned in *Sec. 3.3*, we may compute above equations every a large step ΔT , and if we adopt (5.1) to the most closing four mesh points $(l \pm 1, m \pm 1)$ to (l, m) , which is the same case as illustrated in Fig. 8, we obtain the difference form equivalent to (5.18)

$$\begin{aligned} \left\langle \frac{X}{Y} \right\rangle_{l,m}^{T+1} &= \left[1 - \frac{8L\Delta T}{(\Delta s)^2} \right] \left\langle \frac{X}{Y} \right\rangle_{l,m}^T + \frac{2L\Delta T}{(\Delta s)^2} \left[\left\langle \frac{X}{Y} \right\rangle_{l+1,m+1} + \left\langle \frac{X}{Y} \right\rangle_{l+1,m-1} \right. \\ &\quad \left. + \left\langle \frac{X}{Y} \right\rangle_{l-1,m+1} + \left\langle \frac{X}{Y} \right\rangle_{l-1,m-1} \right]^T. \end{aligned} \quad (5.19)$$

In this case, $L=1.3 \times 10^6$, $T=600$, $\Delta s=8 \times 10^5$ as mentioned in *Sec. 3.3*, so the above coefficients are

$$\left. \begin{aligned} 1 - \frac{8L\Delta T}{(\Delta s)^2} &= 0.99024, \\ \frac{2L\Delta T}{(\Delta s)^2} &= 0.00244. \end{aligned} \right\} \quad (5.20)$$

The meaning of value (5.20) is already given in 3.3.

5.6. The procedure at time step and the arrangement of conjugate lattices

Combining (5.3) and (5.15) we can compute $\zeta_{i,j}$ every odd step and $(X, Y)_{i,m}$ every even step as illustrated in Fig. 9. The elevation point (i, j) is located on such the point $i+j=\text{odd}$ and the current point (l, m) is located on $l+m=\text{even}$, so these two points are adjoining each other as illustrated in Fig. 9, where the dotted line shows the coastal line and at the points ζ and $\bar{\zeta}$ marked with a triangle, the mouth conditions having the same value are given. The Figure 9 is an example for the lalices near Akashi St. But for the mediation of Coriolis parameter the conditions $\triangle$ and $\triangle$ would independently travell over the $(\zeta,$

M, N) and $(\bar{\zeta}, \bar{M}, \bar{N})$ series respectively which are called conjugate lattice series each other. On the other hand, the water is, of course, continuous substance, so both lattice series should be under the same mouth condition. This is the reason why at the two points $\underline{A}$ and $\bar{\underline{A}}$ the same value is given.

All the functions appearing in (5.16) are defined on the same points as $(X, Y)_{i,m}$. Referring to the non-linear term at both east and west and straits, the author supposed that $\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}$ etc.=0, because near both straits the topographic features are nearly symmetric with the normal to stream axis and the velocity reaches its maximum value.

5.7. The stability

Provide that $h \gg \zeta$, then we can rewrite the fundamental equations (3.25), (3.26) in the following form

$$\left. \begin{aligned} \frac{\partial M}{\partial t} &= f'N - gh \frac{\partial \zeta}{\partial x} - e'M, \\ \frac{\partial N}{\partial t} &= -f'M - gh \frac{\partial \zeta}{\partial y} - e'N, \\ \frac{\partial \zeta}{\partial t} &= -\frac{\partial M}{\partial x} - \frac{\partial N}{\partial y}, \end{aligned} \right\} \quad (5.21)$$

where

$$\left. \begin{aligned} f' &= \left[f - \frac{\partial u}{\partial y}, \quad f + \frac{\partial v}{\partial x} \right], \\ e' &= \left[\gamma^2 \frac{|V|}{h} + 2 \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \quad \gamma^2 \frac{|V|}{h} + \frac{\partial u}{\partial x} + 2 \frac{\partial v}{\partial y} \right], \quad (|V| = \sqrt{U^2 + V^2}), \end{aligned} \right\} \quad (5.22)$$

further the inhomogeneous and horizontal mixing terms are dropped. As f' and e' are computed every large step ΔT , the equations (5.21) are linear equations with constant coefficients for a few time steps. Then we can apply FISCHER's method⁽⁶⁾ to the stability for (5.21), which becomes equivalent to the next linear transformation

$$\begin{pmatrix} M \\ N \\ -\sqrt{gh}\zeta \end{pmatrix}^{\tau+1} = G \begin{pmatrix} M \\ N \\ -\sqrt{gh}\zeta \end{pmatrix}^{\tau-1}. \quad (5.23)$$

Neglecting $e' \Delta t \cdot (f' \Delta t)^2$, one of the eigen-values of G has the next absolute value

$$|\lambda_1| = 1 - e' \Delta t \quad (5.24)$$

and if

$$4gh\left(\frac{\Delta t}{\Delta s}\right)^2 < 1 - \frac{e'\Delta t}{2} + \sqrt{1 - e'\Delta t + (f'\Delta t)^2} \quad (5.25)$$

the others become

$$|\lambda_{2,3}| = \sqrt{1 - e'\Delta t + (f'\Delta t)^2}. \quad (5.26)$$

That is, under the condition (5.25) our scheme satisfies the von NEUMANN'S necessary condition for stability

$$|\lambda_i| \leq 1 + O(\Delta t) \quad i=1, 2, 3. \quad (5.27)$$

Usually Δs is previously decided according to the capacity of computer, so from the condition (5.25) we determine Δt , which decides the time required for the computations.

First, putting $e'=0$, $f'=0$, (5.25) becomes

$$4gh\left(\frac{\Delta t_1}{\Delta s}\right)^2 < 2. \quad (5.28)$$

In our case $\Delta s = 8 \times 10^5$, $h_{\max} = 8 \times 10^3$ near Akashi St. then (5.28) gives the next condition for the first approximation of Δt

$$\Delta t_1 < 200 \text{ (sec)}.$$

Second, using the above value, estimate the minimum value of right side of (5.25), which is given by $f'=0$ and the maximum value of e' . For e' ,

$$|e'|_{\max} \leq [\gamma^2 |V|/h]_{\max} + 2[\text{grad } V]_{\max}. \quad (5.29)$$

The maximum current is 4×10^2 at Kurushima St., so

$$[\text{grad } V]_{\max} \approx 0.5 + 10^{-3}.$$

On the other hand $[\gamma^2 |V|/h]_{\max}$ will be seen near the coast. The speed of surges progressing on the land has often researched, however, Dr. Z. NAKAMURA¹⁷⁾ investigated in detail the surges happened in the year 1917, almost 3 m along the coast, which is the largest in Tokyo Bay, and reported that according to the records by tide gauges, the speed of surges rising along the rivers in the city is 12.3~20.0 km/hr. and that by observers' saying, on the land it becomes 15.6 km/hr. If we use the above data $|V| = 4 \times 10^2$ cm/sec. and $h = 3 \times 10^2$ cm, we get

$$[\gamma^2 |V|/h]_{\max} < 4 \times 10^{-3}$$

$$\therefore |e'|_{\max} \leq 5 \times 10^{-3} \quad \text{and} \quad |e'|_{\max} \Delta t \leq 1.$$

Then from (5.25) we get the condition for the second approximation of Δt

$$4gh\left(\frac{\Delta t_2}{\Delta s}\right)^2 < \frac{1}{2} \quad \text{or} \quad \Delta t_2 < 100 \text{ sec}.$$

In the real case Δt may exist between Δt_1 and Δt_2 , however, the writer, standing the safety side, takes Δt_2 itself for the real time step.

According to the results of our computations, $|e'|_{\max}$ is one order smaller

than the above estimated value, and indeed, from (5.24), (5.26) and (5.27)

$$|e'| \Delta t \ll 1$$

is required, which restricts the frictional and velocity gradient term, above all, the minimum value of h .

It is analitically proofed that our scheme satisfies the von NEUMANN's necessary condition and also numerically examined that it is computationally stable, however, to obtain the sufficient condition is remained to be studied. Above all what happens in the case $e' < 0$, where $|\lambda_t|$ exceeds unity, is unknown. This problem will be numerically examined and discussed in the next paper.

Chapter 6. The results of computations

The meshes for the Central Part of Inland Sea is shown in Fig. 10, where the numeral denotes the depth below the mean sea-level, the black round means the position of selected station whose localities (I, J) are seen in Table 3, and the dotted line gives the coastal line, with which the topographic feature for our area on computations is represented as shown in Fig. 11. The computed elevations and current (x, y component) at all the mesh points are printed in the map every hour and those of selected stations are tabled every ten minutes together with the computed atmospheric pressure, wind speed and direction.

To compare those computed results with the observations is the most important matter. In this area many permanent tidal stations are located, which coincide with the selected stations mentioned above, and fortunately the writer could gather the reported materials, observed data and tide gauge records in the most cases investigated in this paper. In this chapter the astronomical tides are firstly discussed, this case is the most important because of being our basic model and proving rationality of our method. Having a look at the results of weather and surges in the cases as listed in *Sec. 4.1*, the author discussed the surges caused by the "Toya-maru" typhoon, with which the writer mentioned in chapter 1. In this case we can see the most interesting phenomena in both observations and computations which remain us problems to be studied in the future.

6.1. The astronomical tides

The characteristics of tides in this area is chiefly decided by its topography, which is stated in chapter 1, showed in Fig. 1 and the general aspect for tides viewing from the observations is as follows: Harima Sea is communicated with

outer seas by Akashi and Naruto straits, however, the latter's width is only 1.3 km, so the tides in this sea is ruled by the tidal waves coming through Akashi Straits whose width is 4 km. The semi-diurnal tide coming in from Kii Channel is, in the passage through Osaka Bay, so damped that at Akashi Straits the amplitude reduces to half and the phase lags by 3 hours comparing with those of open sea. On the contrary the diurnal tide shows little damped oscillation. These circumstances are illustrated in Fig. 12, a, b¹⁸⁾. Consequently in Harima Sea the diurnal tide is predominant, however, the high water level is only 50 cm above the mean sea level, which arises near the low water in Kii Channel. This fact causes at springs nearly 1.4 m sea level difference on the both side of Naruto Straits and makes the strong current of 500 cm sec⁻¹, famous as well as the Maelstrom in the Lofoten Is. of Norway and the Charybdis at St. Messina in Italy.

The tides in Hiuchi Sea is mainly ruled by the tidal waves coming through Kurushima Straits. On the out side of here the semi-diurnal tide is predominant and its high water level reaches nearly 150 cm above the mean sea level, which causes so strong current at Kurushima Straits in both velocity and volume that it principally affects the tides in all the Central Part of Inland Sea.

It is very remarkable that, contrary to the example in *Sec. 2.2*, in this area the wave velocity of semi-diurnal tide is much larger than that expected from the progressive free long wave, except near Akashi and Kurushima Straits where it is much smaller. This fact means that the tidal wave in our seas is not progressive, but stationary one as examined by computations.

The computations for the semi-diurnal tides ($M_2 + S_2$) in this area are made as mentioned in *Sec. 2.8*, from the initial state (neither elevation nor velocity in all the mesh points) to the fourth period which gives us the converged tidal waves at any point, this passage is illustrated in Fig. 13. The time variations of elevations and currents at the three straits are shown in Fig. 14, a, b, c.

The epoch in Fig. 13~14 is the time of mean sea level at Hashihama. The comparisons between observations and computations at all the selected stations are shown in Table 3, where the epoch is the time of high water at Hashihama and the values are measured from their mean values. In the observation column the high water level, maximum flow in (+) [or west (w)] current velocity and their occasions are given, where the lag is that of M_2 and the value is $M_2 + S_2$, both are reckoned from the harmonic constants. In the computation column, in addition to those of observation, the author shows the low water level (—) and maximum flow out (—) [or east (E)] current velocity.

We see from Fig. 13, 14 and Table 3 that the curve of elevation and current at any point is not symmetrical one with its mean value, as expected from *Sec.* 2.2 or Fig. 3, 4. That is, the strong ebb current at Kurushima Straits makes strong flood current against any station in Hiuchi Sea and causes the sharp high water and flat low water. This is so strong that it affects the tides in Harima Sea where the difference between high and low water level is small. We can also see this non-linear effect strongly in Fig. 5.

Table 3. Comparison between observation and computation [Cf. Fig. 10, 11].
epoch: high water time at Hashihama, negatime: occation before epoch

	Station			Observation		Computation		
	No.	Name	I, J	h m	cm (sec ⁻¹)	h m	cm (sec ⁻¹)	cm (sec ⁻¹)
Time and Hight of High Water, and Law Water Level (—)	1	Akashi	9, 2	—1 35	25	—1 35	25	—25
	2	Himeji	2, 7	0 56	40	2 50	46	—44
	4	Ushimado	4, 21	1 13	65	1 55	65	—63
	5	Uno	6, 25	1 13	89	1 55	94	—92
	6	Mizushima	2, 31	1 21	140	2 25	159	—136
	7	Kasaoka	2, 37	1 23	152	2 20	164	—146
	8	Onomichi	3, 42	1 04	148	2 20	157	—140
	9	Imabari	10, 49	0 54	139	1 50	114	—118
	10	Hashihama	9, 50	0 00	149	0 00	149	—149
	11	Niihama	16, 45	1 02	149	2 25	134	—130
	12	Kannonji	12, 35	1 13	140	2 20	150	—136
	13	Sakaide	10, 31	1 23	130	2 25	127	—119
	14	Takamatsu	10, 25	1 19	84	2 10	94	—96
	17	Tonosho	7, 22	1 13	50	1 55	72	—68
	15	Sanbonmatsu	17, 16	1 31	45	2 10	54	—53
	16	Ei	12, 7	1 35	31	1 55	37	—38
Max. Current	18	Akashi St.	9, 3	—1 35	+210	—1 40	+158	—164
	19	Bisan St. (E)	9, 21	—1 50	W90	—1 10	W104	E109
	22	Kurushima St.	10, 50	—1 30	+365	—0 50	+336	—325
				+ flow in W west		— flow out E east		

The most marked gap in above comparisons is the phase lag near both Akashi and Kurushima St. For example, the lag required to pass Kurushima St. is 54 minutes in observation and 110 minutes in computation. If we eliminate this difference, the computed results explain fairly well the tidal phenomena in this

area. According to the maps (Fig. 15, I~XII) for distributions of elevation and current obtained every hour from this computations, the schematic explanation for the semidiurnal tide in the Central Part of Inland Sea is as follows:

1. One hour before the upper culmination here, the sea level reaches the high water and the current stops in the whole area (Fig. 15, I).
2. It begins the sea-level to fall and the current to flow out from this area through both Kurushima and Akashi Straits. The turning line of east and west current gradually moves in Hiuchi Sea from west to east. The current velocity is increasing. (Fig. 15, II~III).
3. Three hours after the high water the elevation reaches the mean sea-level and the current gets the maximum velocity in the whole area. The turning line of currents reaches near the western part of Bisan Straits (Fig. 15, IV).
4. The elevation and current velocity is decreasing. The turning line moves through Bisan Straits to east in Harima Sea. (Fig. 15, V~VI).
5. Six hours after the high water the elevation reaches the low water and the current stops in the whole area. (Fig. 15, VII).
6. It begins the sea-level to rise and the water to flow into this area through both Kurushima and Akashi Straits. The meeting line of the two currents moves in Hiuchi Sea from west to east. The current velocity is increasing (Fig. 15, VIII~IX).
7. Nine hours after the high water, the sea again reaches the mean sea-level and the currents get the maximum velocity in whole the area. The meeting line reaches near the western part of Bisan Straits. (Fig. 15, X).
8. The elevation is rising, the current velocity decreasing. The meeting line moves through Bisan Straits to east in Harima Sea. (Fig. 15, XI~XII).

6.2. *The meteorological computation*

The comparisons between observed and computed weather results for each typhoon are shown in Fig. 16~20 each consisting of four figures a~d. In Fig. a of Fig. 16~20 the observed pressure distributions (mb) as function of distance (km) from the typhoon's center are shown, which are obtained from many weather stations. In each figure the curve shows the theoretical pressure distribution from (4.1) at the time when the typhoons most closed to our area. In our weather computations the typhoon more than 500 km far from this area is

out of problem as mentioned in *Sec. 4.3*. In Fig. b, c, d of Fig. 16~20 the comparisons of pressure and wind variation, a arrow showing speed and direction (upper, north), are shown at three main weather stations, that is, Himeji located in the eastern part, Takamatsu in the central part and Matsunaga (near Onomichi) in the western part of our area. The computed wind speed is about 1.5 times stronger than observed one as often reported from the observations by stations on the land and ships over the sea¹⁹⁾ under the typhoon.

Generally speaking, the theoretical value for the pressure variation is in good agreement with observations, however, we can often see the disaccordance in the wind direction comparisons, which is chiefly caused by our meteorological computations based on the formula for the pressure distribution.

6.3. *The storm surge computation*

The surge computations are made with the initial and boundary conditions as mentioned in *Sec. 2.8*. The comparisons between the observed surges deviated from the astronomical tide which is predicted by the tide table, and the computed surges deviated from the sea-level obtained from the tidal computations as mentioned above, are shown in Fig. 21~24 at main selected stations in the four cases of Ruth, 5412, 6016 and 2nd Muroto typhoon, and in Fig. 25 at all the stations in the case of "Toya-maru" typhoon. The main stations are Himeji, Ei or Ushimado in Harima Sea, Takamatsu or Uno in Bisan Straits, Kasaoka or Onomichi on the north side and Niihama on the south side of Hiuchi Sea.

Except Niihama in the case of 5412 typhoon computed surges fairly well agree with observed results, however, in each case the initial part of computed surges are too small, which is mainly caused by our initial conditions putting surges and currents by the typhoon to be all zero. In the real case the currents caused by the typhoon is known to appear much earlier than its approachments, which cannot be represented by our mouth condition based on the surges, that is, the variation of sea-level, and indeed the currents under the typhoon have hardly been observed.

6.4. *The Toya-maru Typhoon*

In this case the most interesting, three phenomena are obtained. First is shown in Fig. 25, r, s, which are obtained by the self-recording tide gauges at Kasaoka and Fukuyama (near Kasaoka), presented through the courtesy of Mr. N. Yamada, 6th Maritime Safety Head Quarters. They may be, of course not the

seismic waves, the seiches in Kasaoka Bay and the mouth of river which cannot be figured by our 4 km meshes. The second is shown in Fig. 25, d, e, f, m, n, that is, the oscillations along Bisan Straits are caught by both observations and computations at three tidal stations, Uno, Takamatsu and Tonosho along Bisan Straits and the corresponding currents are computed at three narrows, Bisan St. (East) (9, 21), Bisan St. (Center) (18, 26) and Okayama Channel (6, 24). The third is the seiches in Hiuchi Sea, which is also caught by both in observations and computations at Mizushima, Kasaoka, Onomichi and Niihama as shown in Fig. 25, g, h, i, j. To make clear this mechanism, the difference of observed and computed sea-level between Onomichi and Niihama is shown in Fig. 25 o, the computed current deviation from astronomical tidal current at the center of Hiuchi Sea (10, 42) is shown in Fig. 25 p, the difference of computed atmospheric pressure between Niihama and Matsunaga and the south component of computed wind velocity at Matsunaga (Matsunaga is located near Onomichi) are shown in Fig. 25 q. That is, this seiches are caused by the strong wind stress and pressure fall passed through Hiuchi Sea like a shock wave with the speed 150 km/hour or 40 m/sec of this typhoon as shown in Fig. 1., and have led the oscillations in Bisan Straits as mentioned above.

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Fig. 1. The Seto Inland Sea, tidal stations (the number coincides with that in Fig. 11 or table 3) and path of typhoon (the numeral means the position of center every hour). [Cf. Chapter 1, and *Sec. 4.1*]

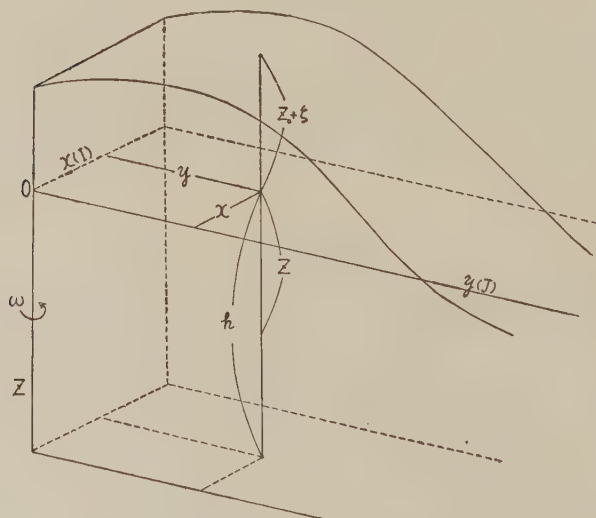


Fig. 2. The co-ordinate system [Cf. Chapter 2]

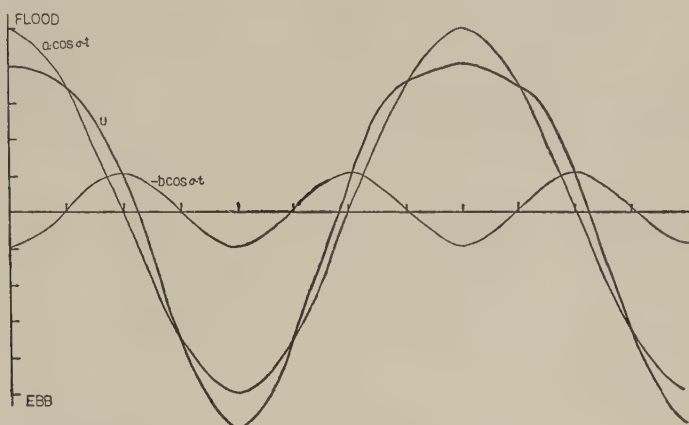


Fig. 3. The time variation of current velocity at a fixed point in a tidal river. The positive, flood and negative, ebb. [Cf. Sec. 2.2 and 6.1]

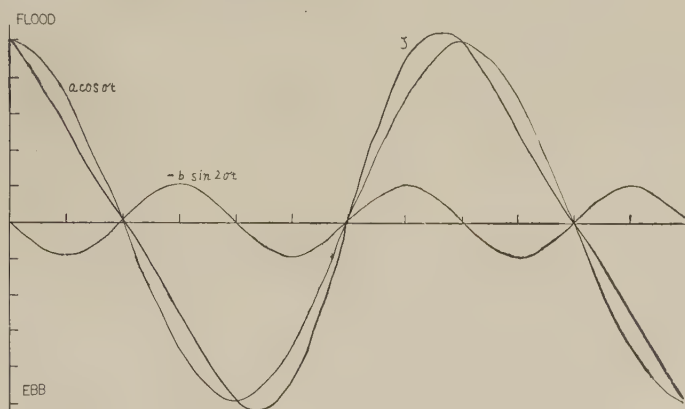


Fig. 4. The time variation of elevation at a fixed point in a tidal river. [Cf. Sec. 2.2 and 6.1]

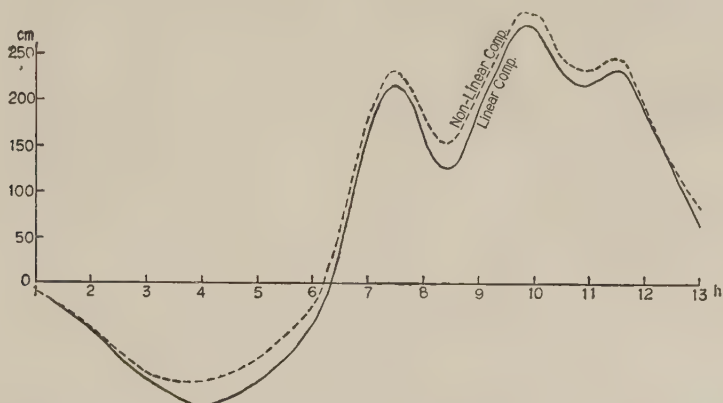


Fig. 5. The time variation of elevation at Mizushima in the case of Ise Bay typhoon taking the course of Toya-maru typhoon, where the linear and non-linear computations are compared. [Cf. Sec. 2.2 and 6.1]

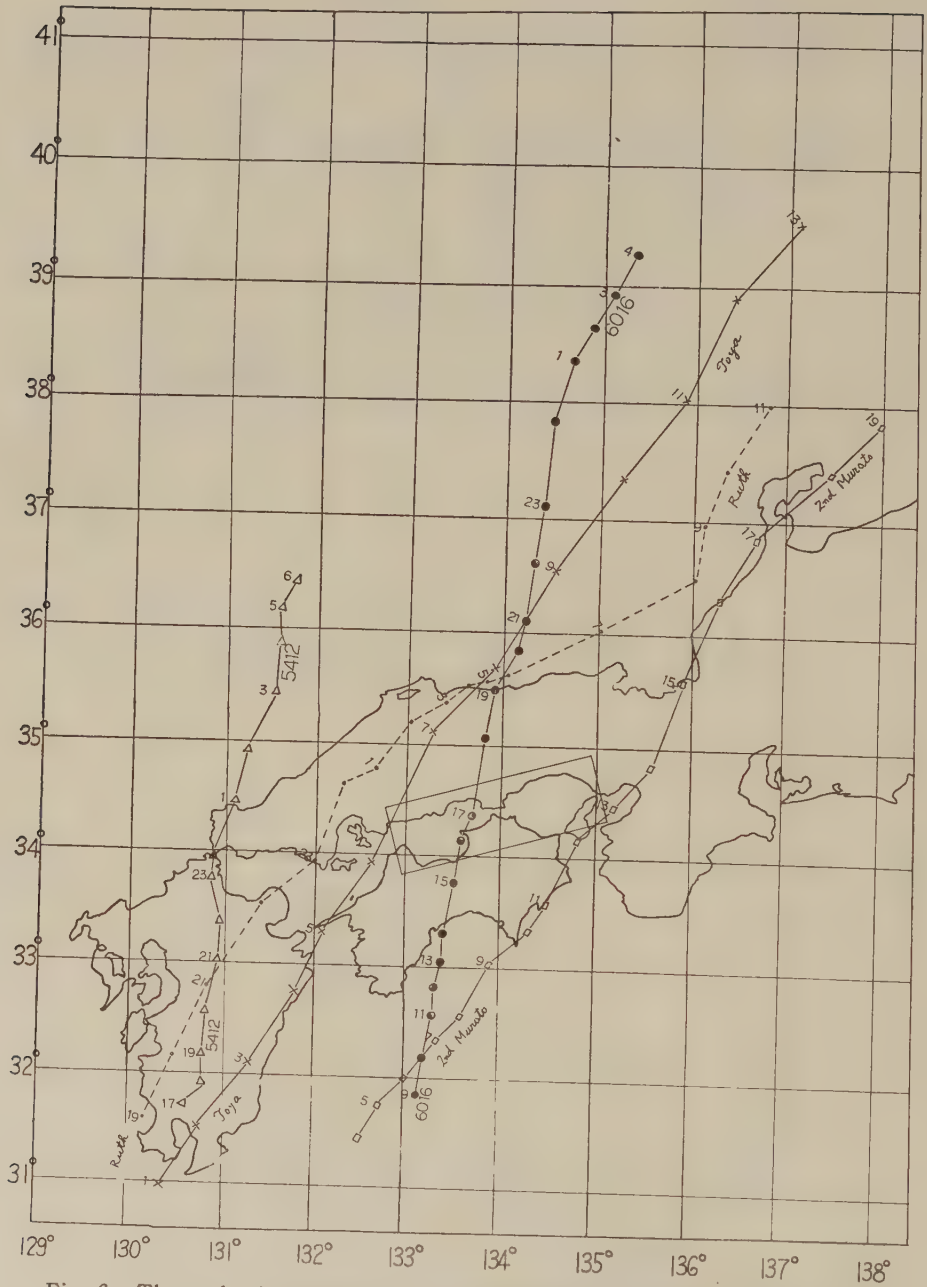


Fig. 6. The path of typhoon, its every hour position and computed area (in the rectangular basin). [Cf, Sec. 4.1]

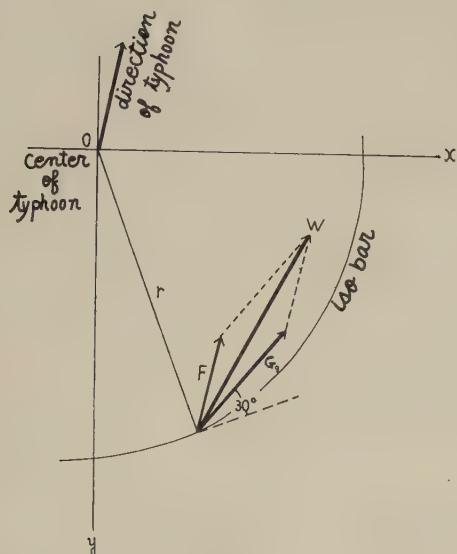


Fig. 7. The wind system, F is the field wind, G the symmetric wind. [Cf. Sec. 4.3]

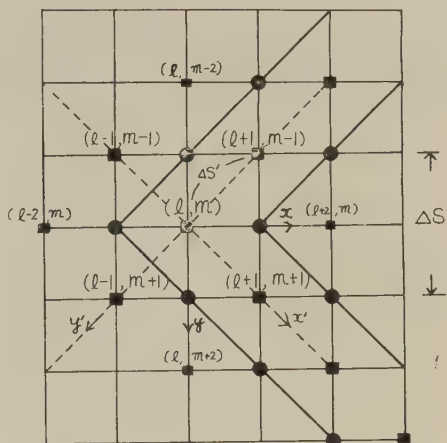


Fig. 8. The schematic illustration to obtain the difference form for horizontal mixing and non-linear term, the broad line shows the sharp edged coastal line. [Cf. Sec. 3.3, 5.3 and 5.5]

YUJ51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35 34 33 32 31 30 29 28

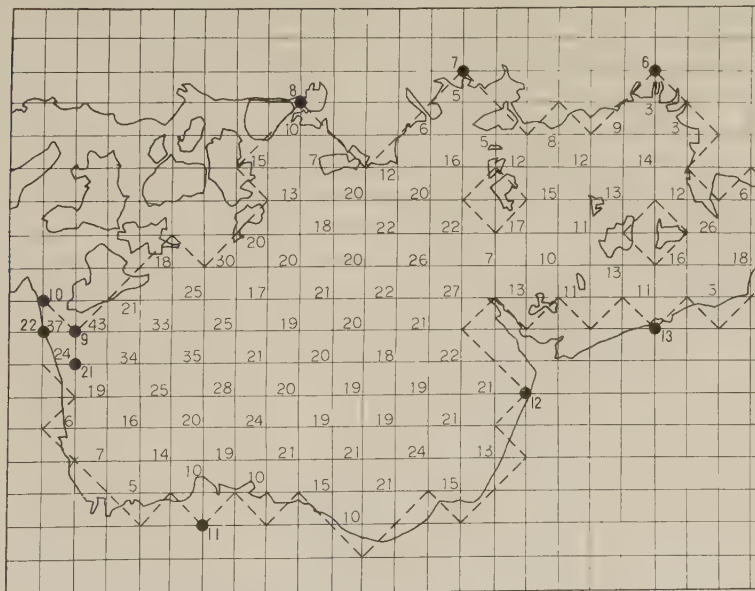


Fig. 10. The latticed form of computed area, where the numeral shows the depth below mean sea-level, the black round with number means the selected

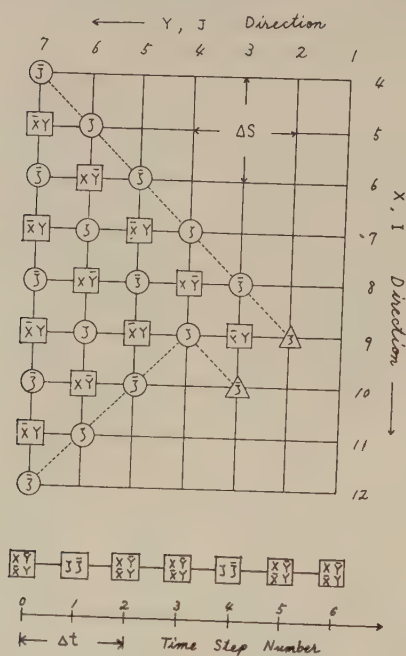
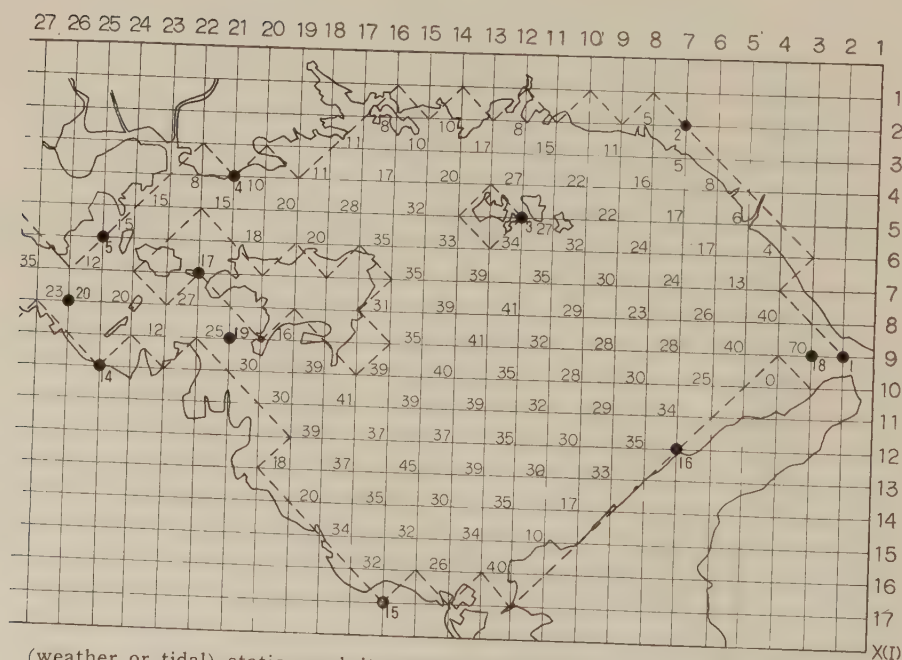


Fig. 9. The time step procedure and arrangement of lattices. [Cf. Chapter 5 and Sec. 5.6]



(weather or tidal) station and its station number (coincide with that in Fig. 1, Fig. 11 and Table 3). The dotted line represents the coastal line. [Cf. Chapter 6]

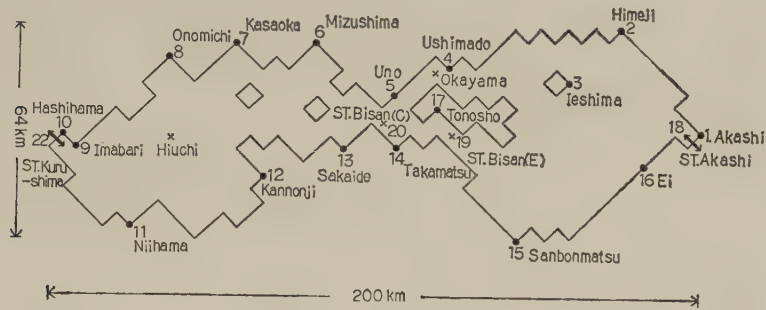


Fig. 11. The coastal line in latticed form. [Cf. the explanation for Fig. 10]

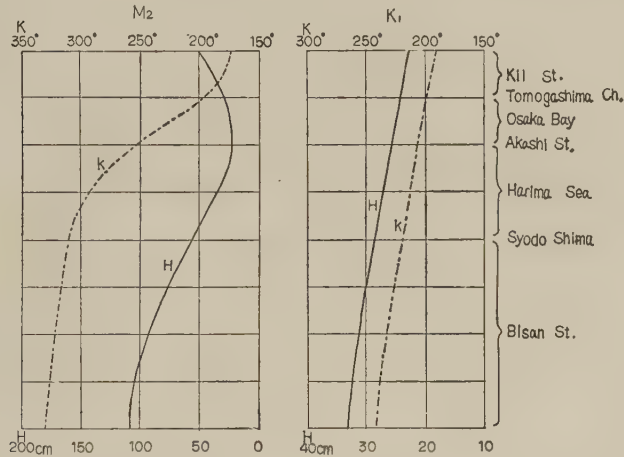


Fig. 12 (a, b). The space variation of amplitude H and phase lag K for M_2 and K_1 in Harima Sea. [Cf. Sec. 6.1]

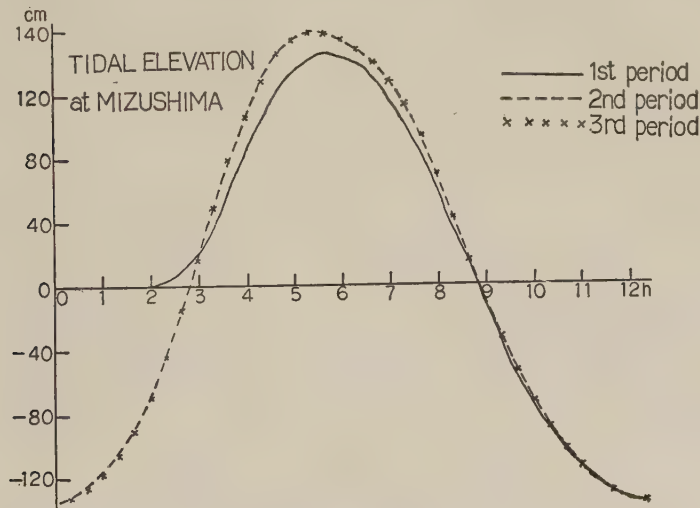


Fig. 13. The passage of computations to obtain the converged form for tidal elevation at Mizushima. The epoch is situated at the time of mean sea-level at Hashihama, [Cf. Sec. 2.8, 6.1 and Fig. 11]

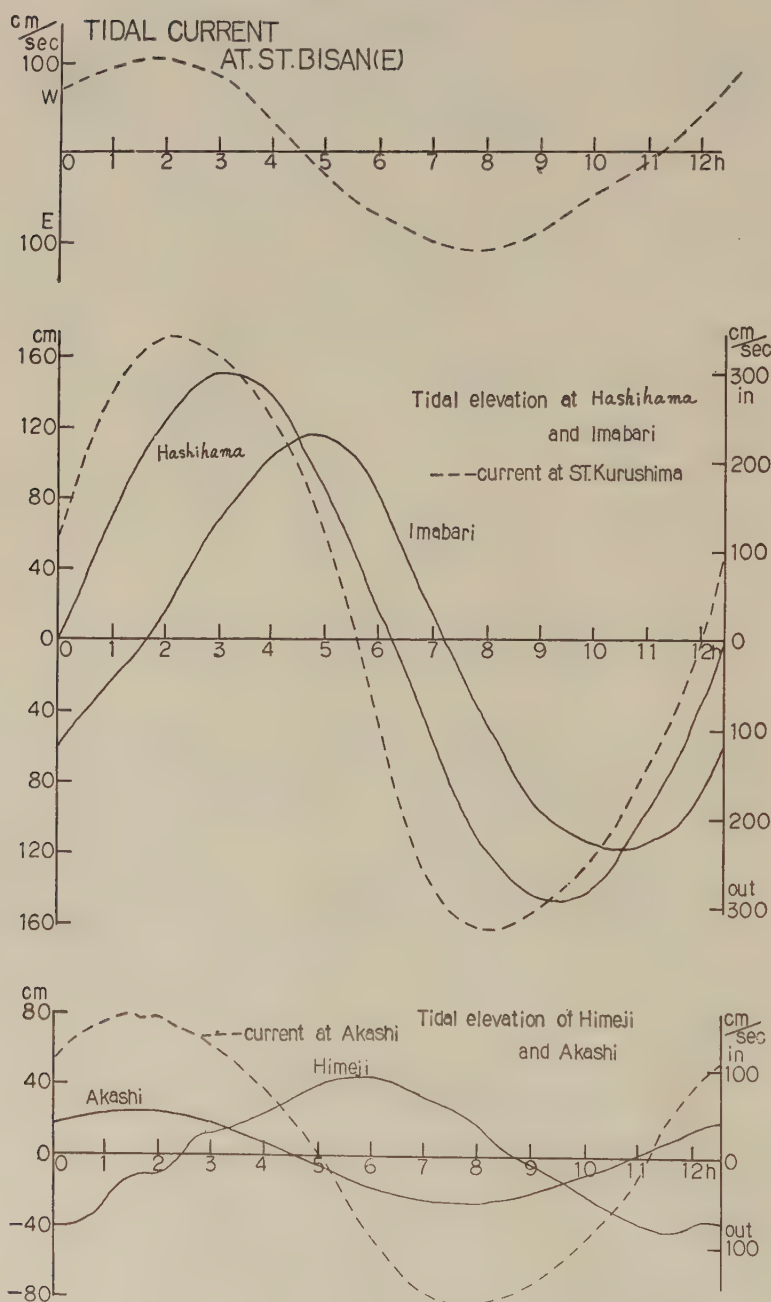


Fig. 14 (a, b, c). The computed tidal elevation and current at Akashi, Bisan and Kurushima Straits. The epoch is the same in Fig. 13. [Cf. Sec. 6.1 and Fig. 11]

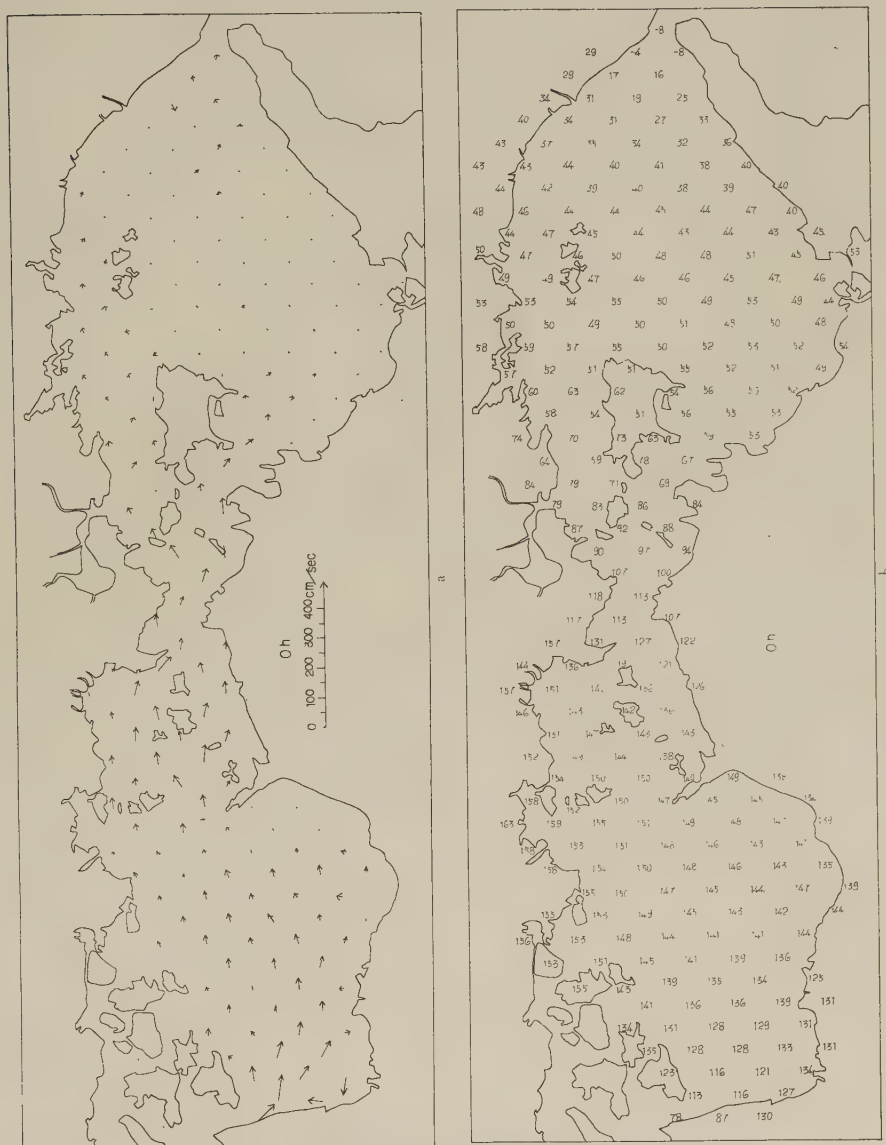


Fig. 15-I. The distribution of computed tidal current and elevation at zero hour. The epoch is situated at high water time. [Cf. Sec. 6.1]
(Left side: North)

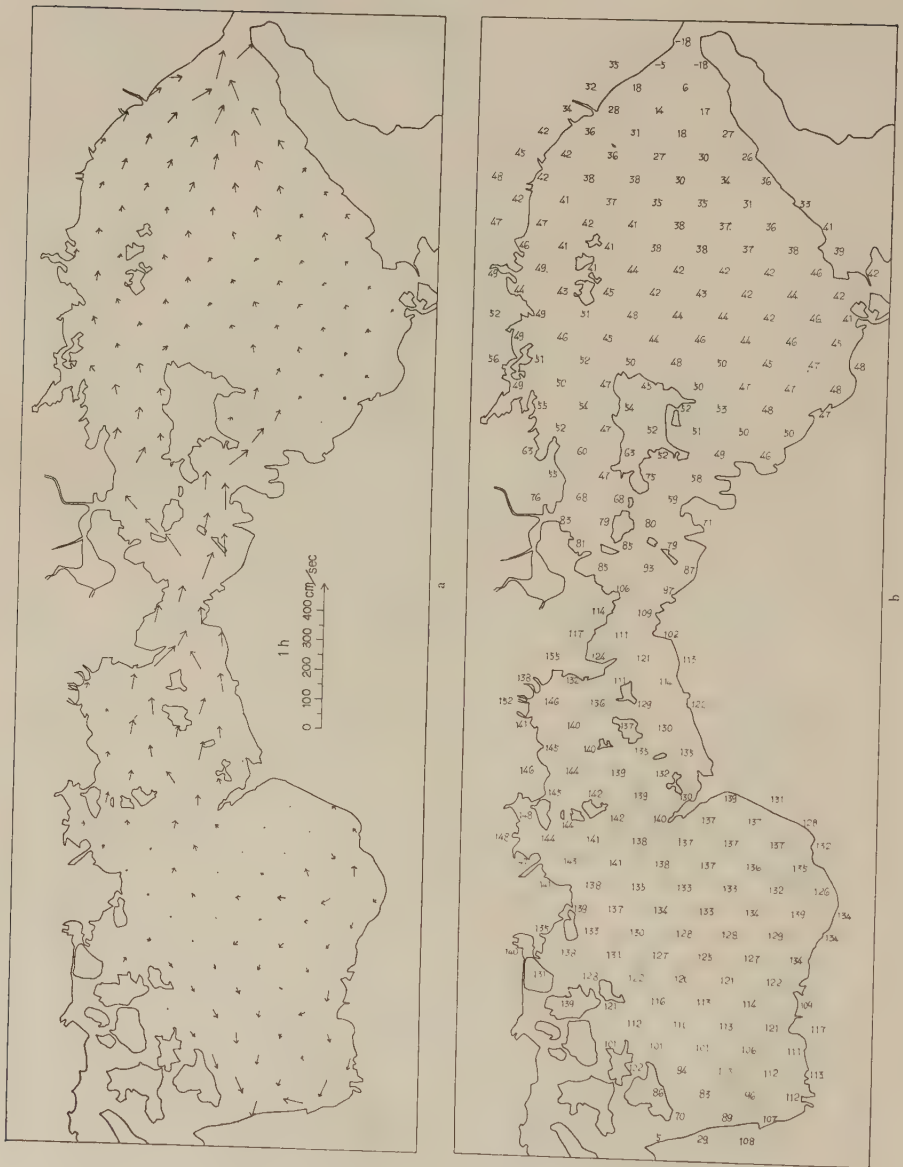


Fig. 15-II. At 1 hour. See explanation for Fig. 15-I.

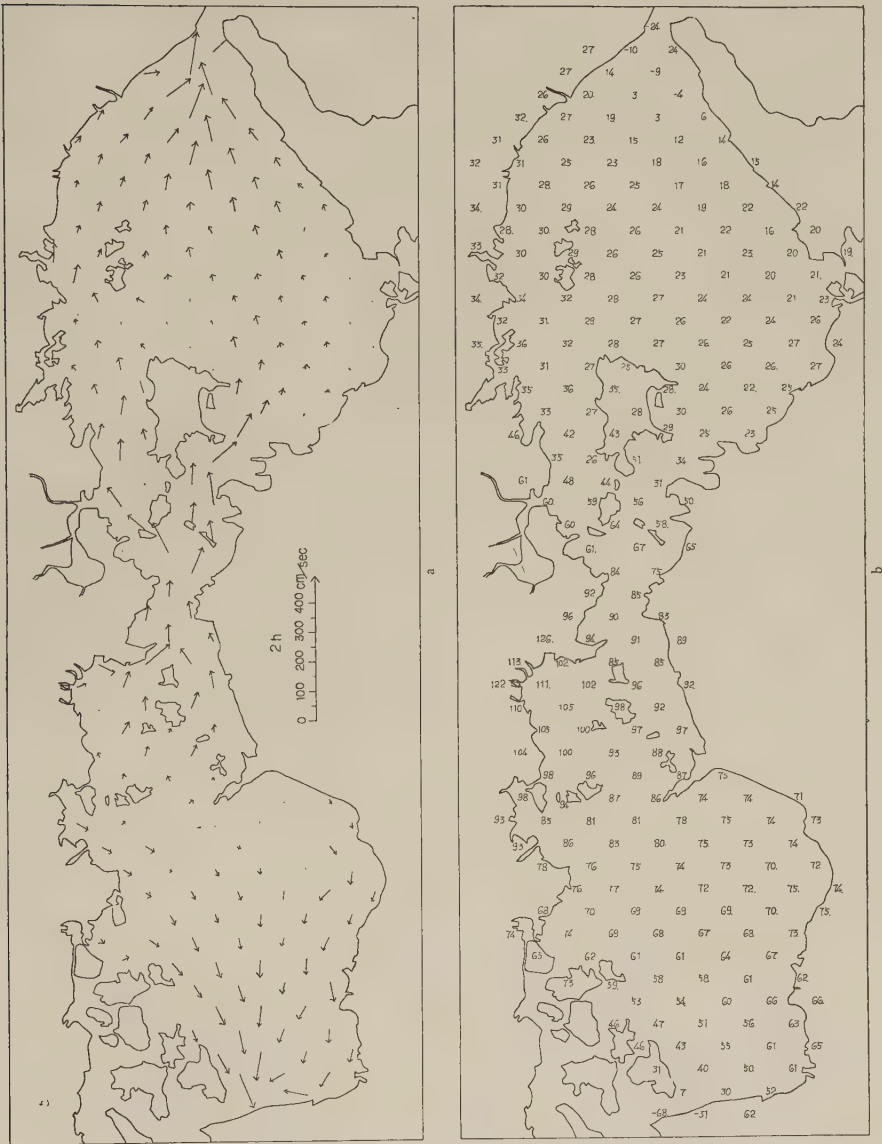


Fig. 15-III. At 2 hour. See explanation for Fig. 15-I.

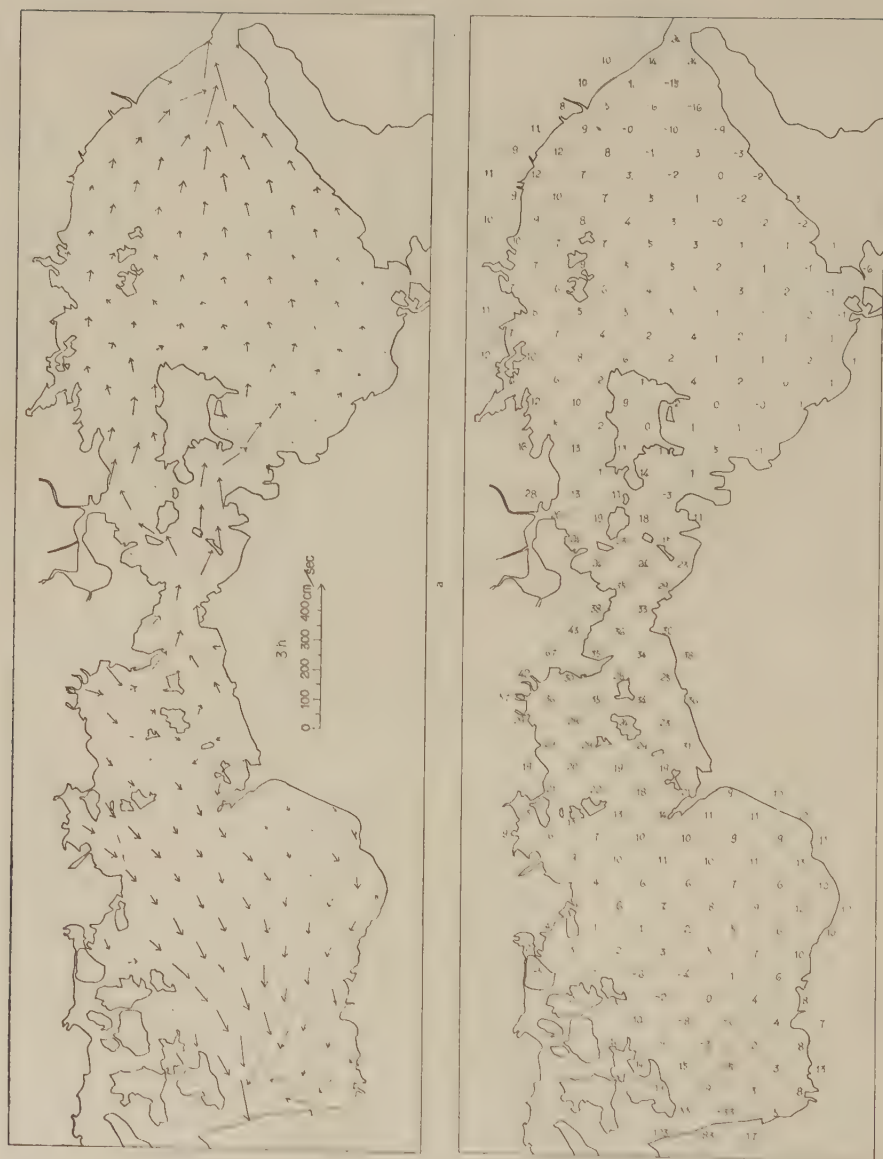


Fig. 15-IV. At 3 hour. See explanation for Fig. 15-I.

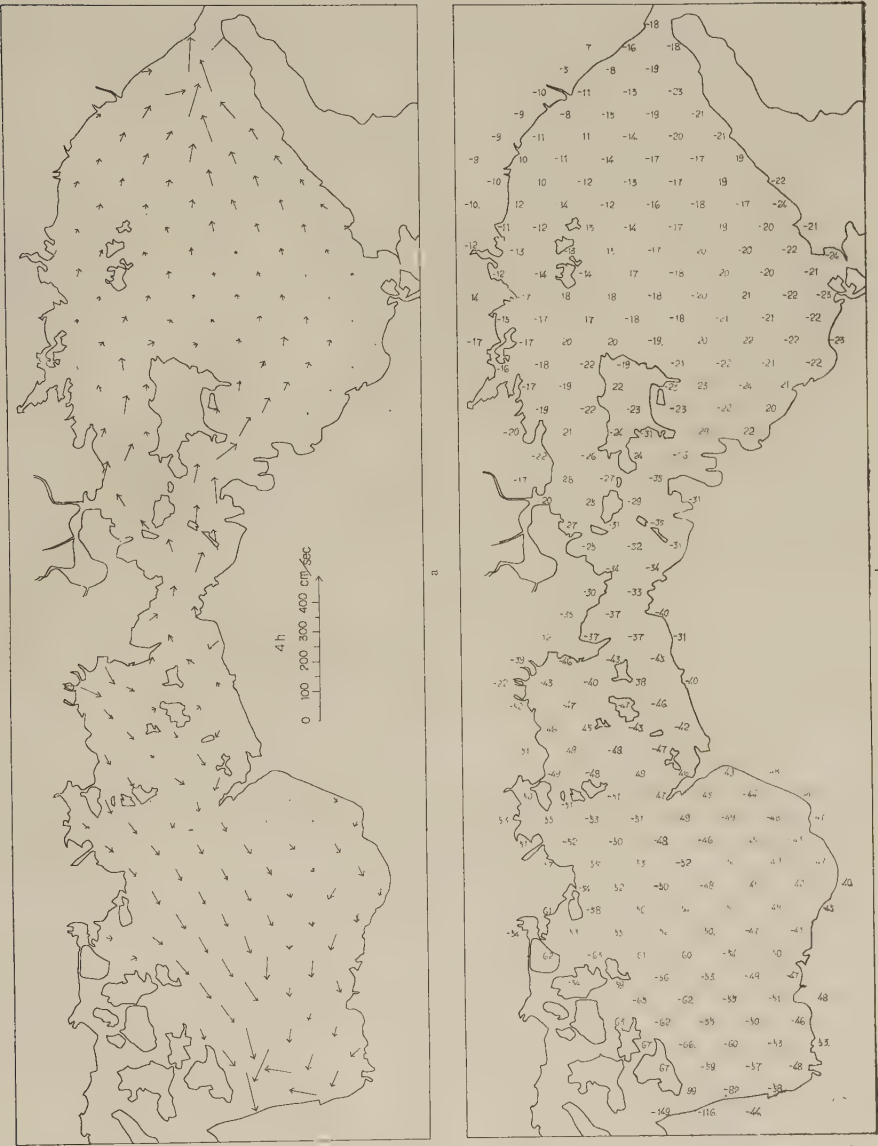


Fig. 15-V. At 4 hour. See explanation for Fig. 15-I.

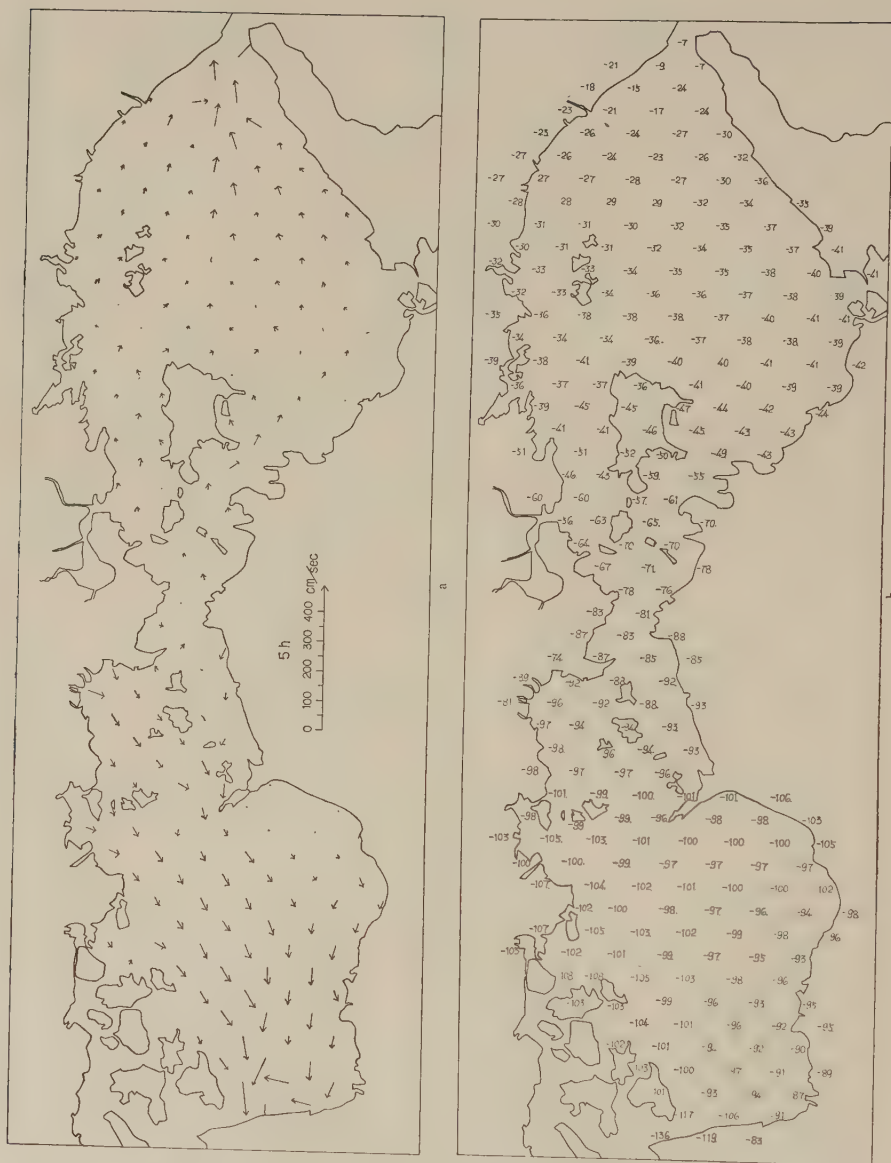


Fig. 15-VI. At 5 hour. See explanation for Fig. 15-I.

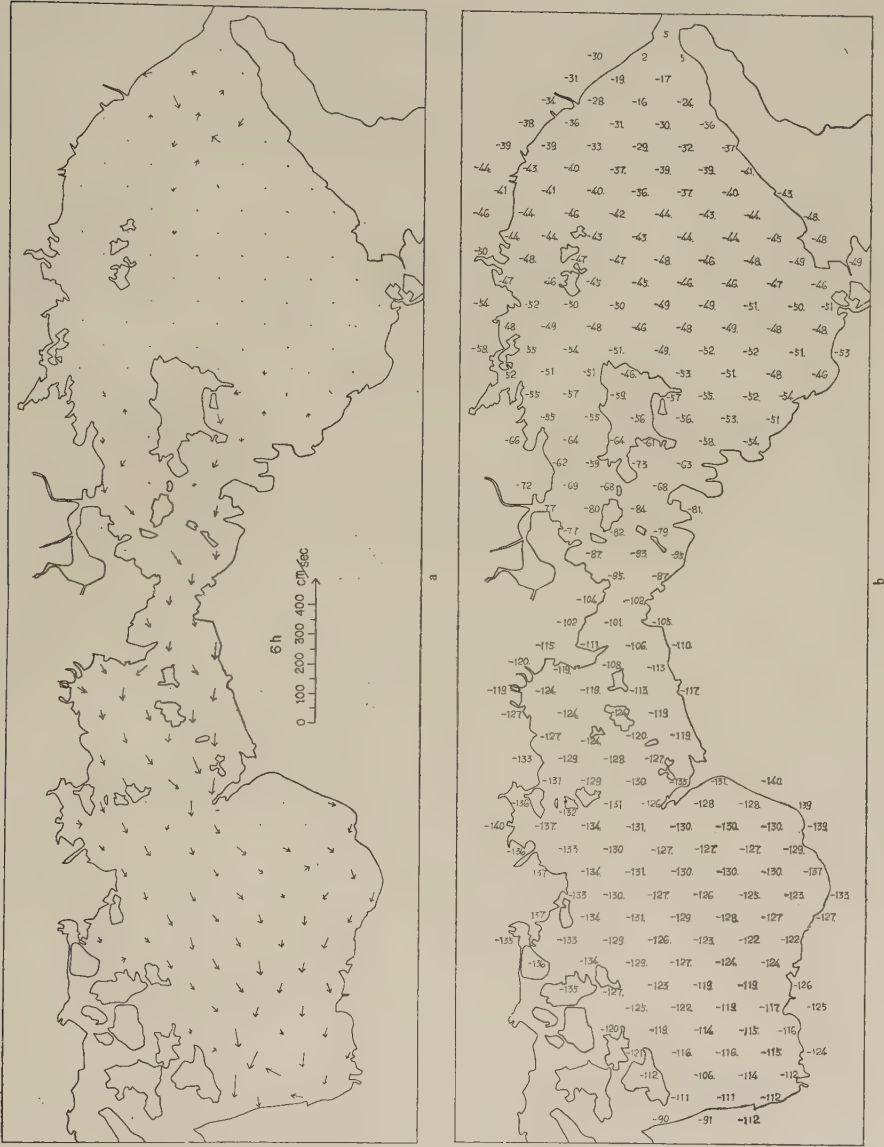


Fig. 15-VII. At 6 hour. See explanation for Fig. 15-I.

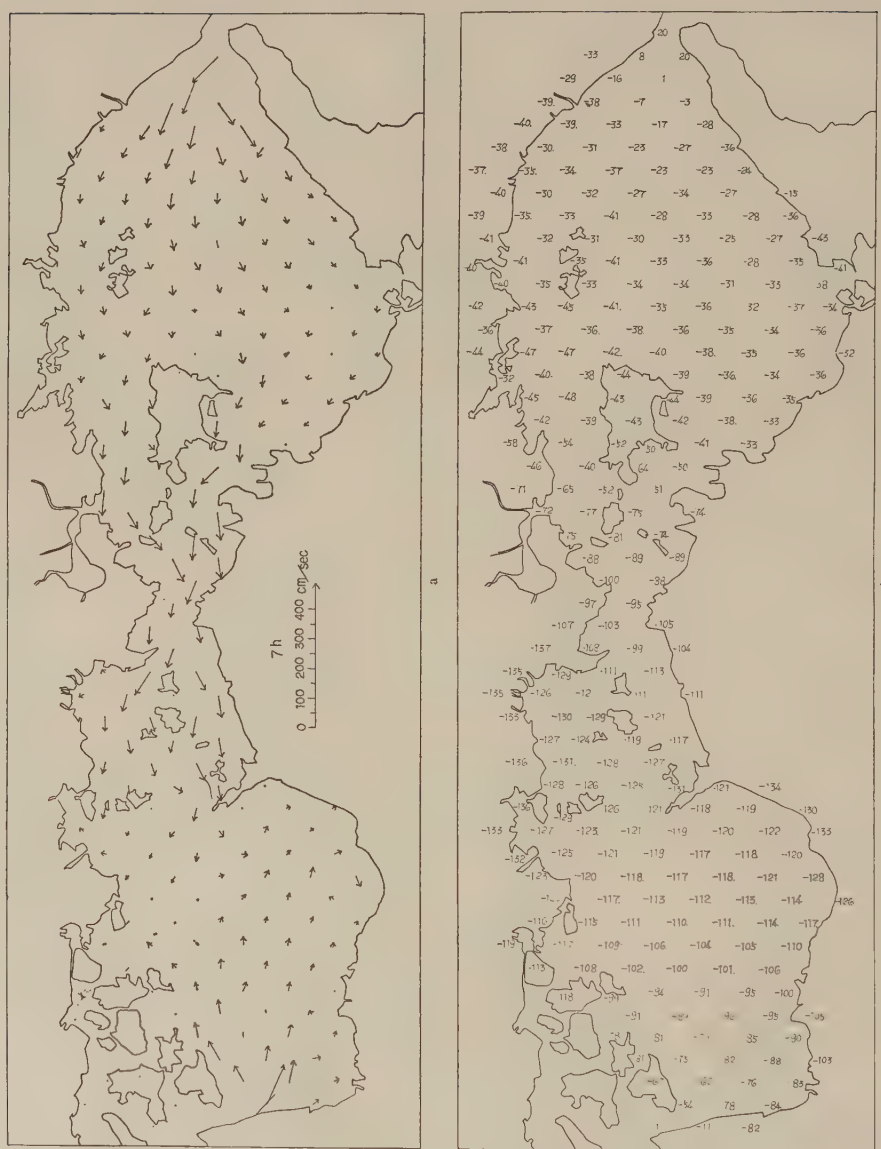


Fig. 15-VIII. At 7 hour. See explanation for Fig. 15-I.

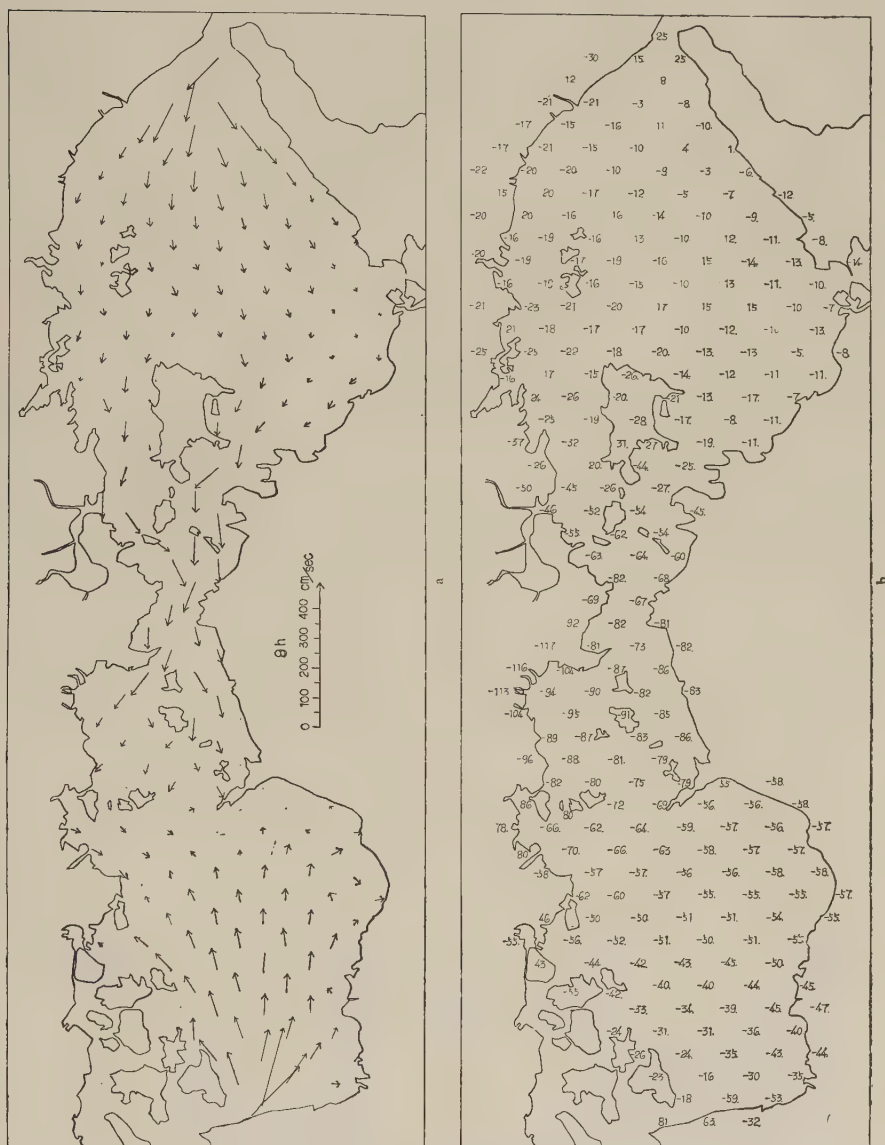


Fig. 15-IX. At 8 hour. See explanation for Fig. 15-I.

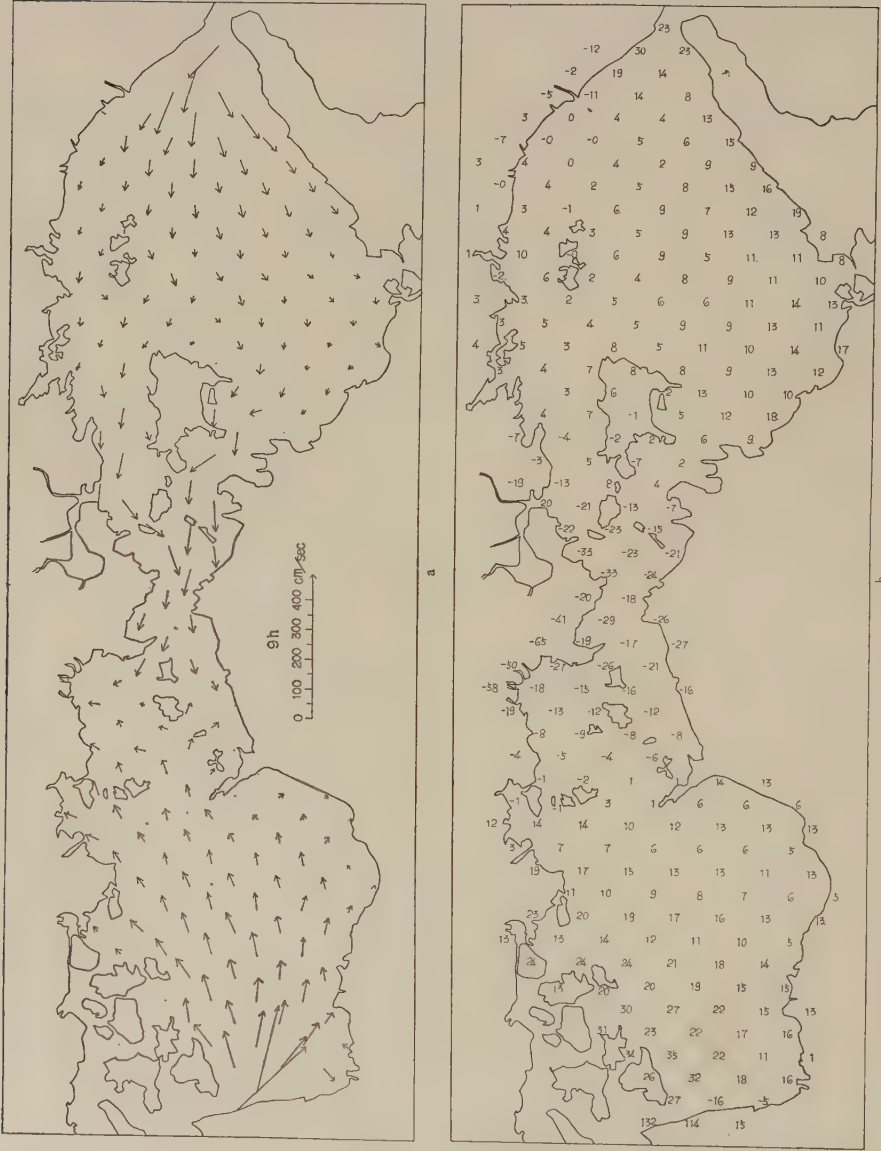


Fig. 15-X. At 9 hour. See explanation for Fig. 15-I.

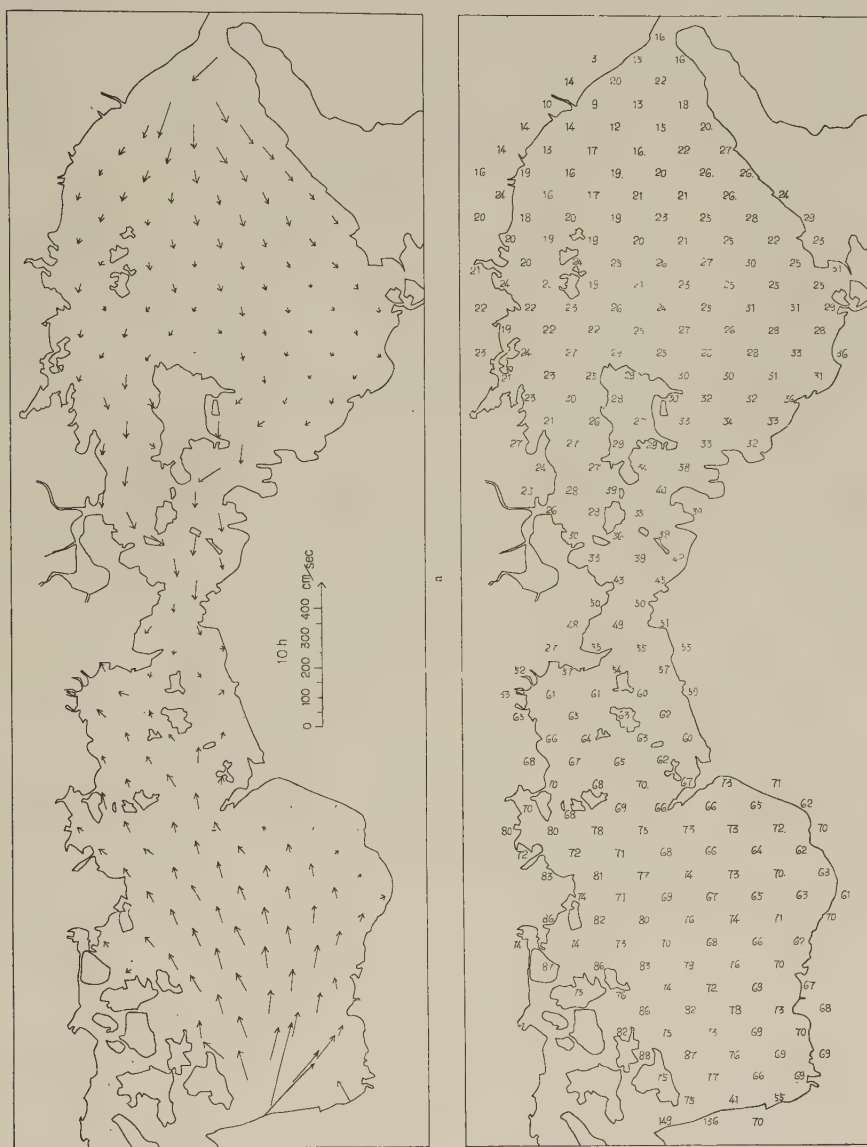


Fig. 15-XI. At 10 hour. See explanation for Fig. 15-1.

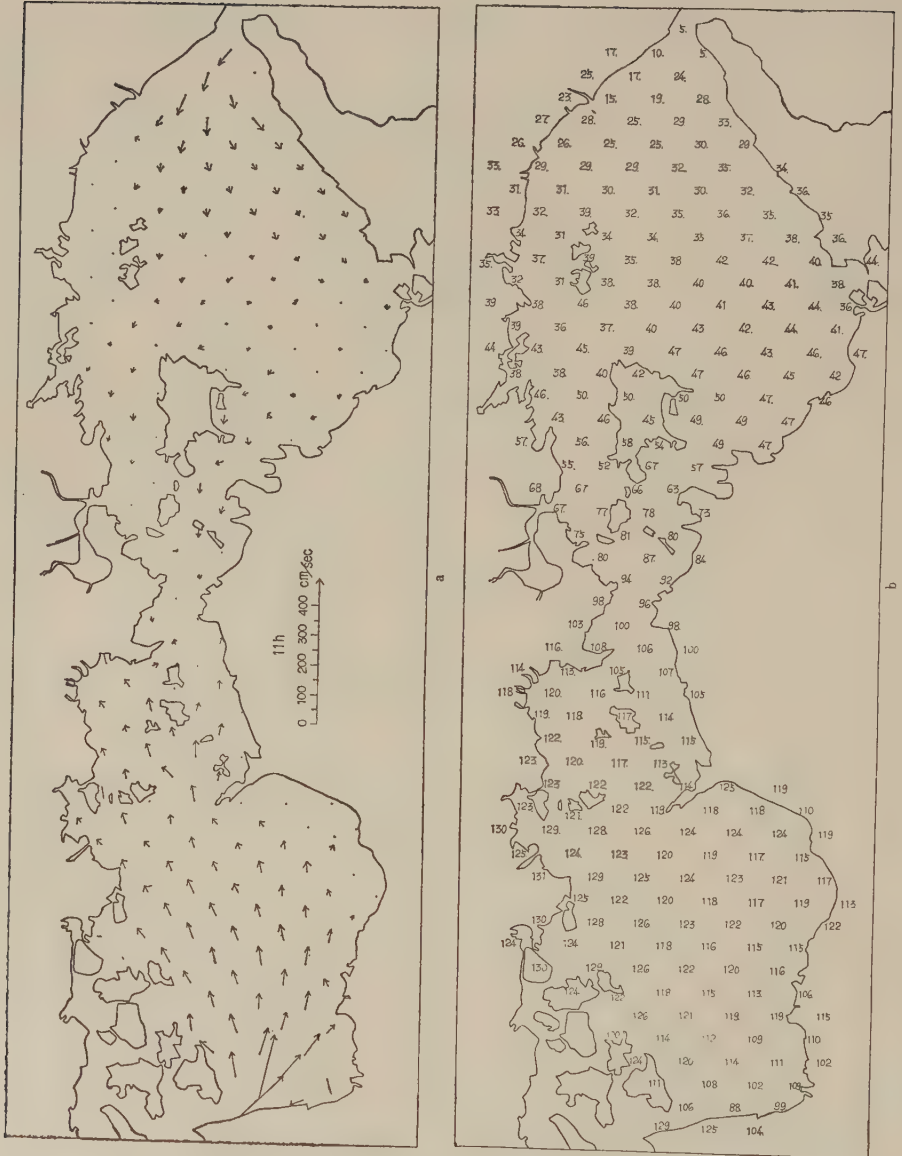


Fig. 15-XII. At 11h. See explanation for Fig. 15-1.

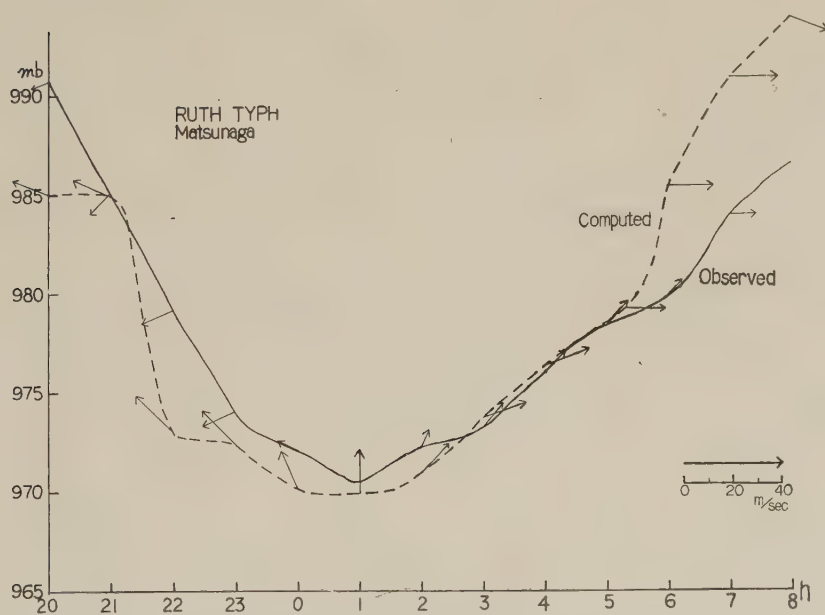
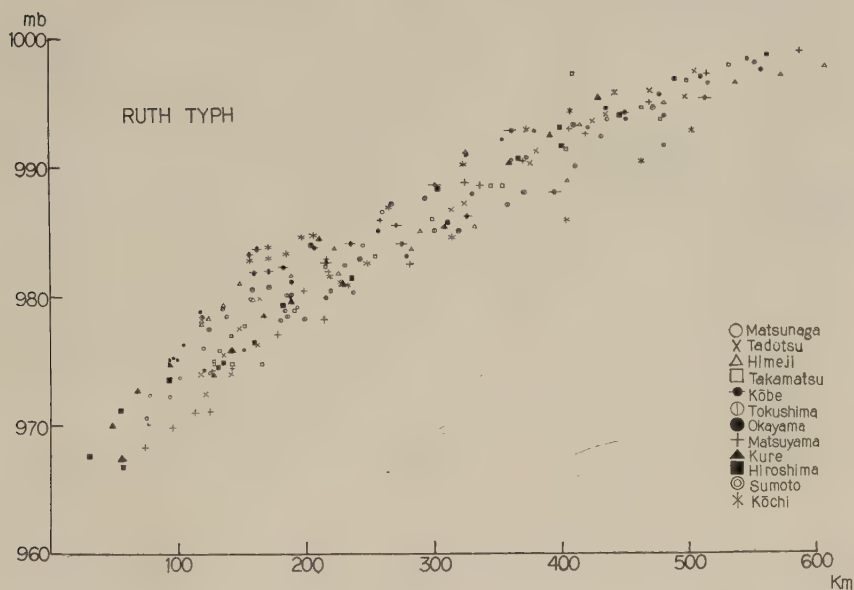


Fig. 16 (a, b). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. Ruth typhoon.

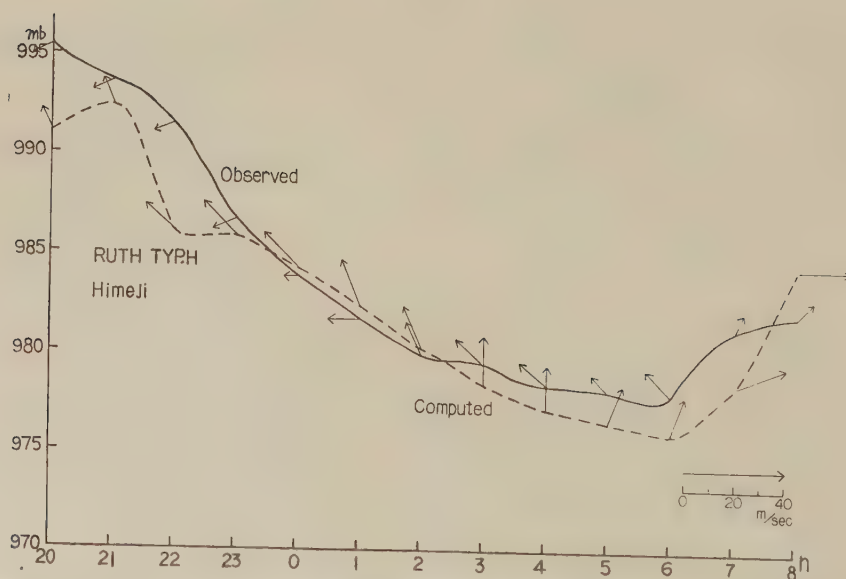
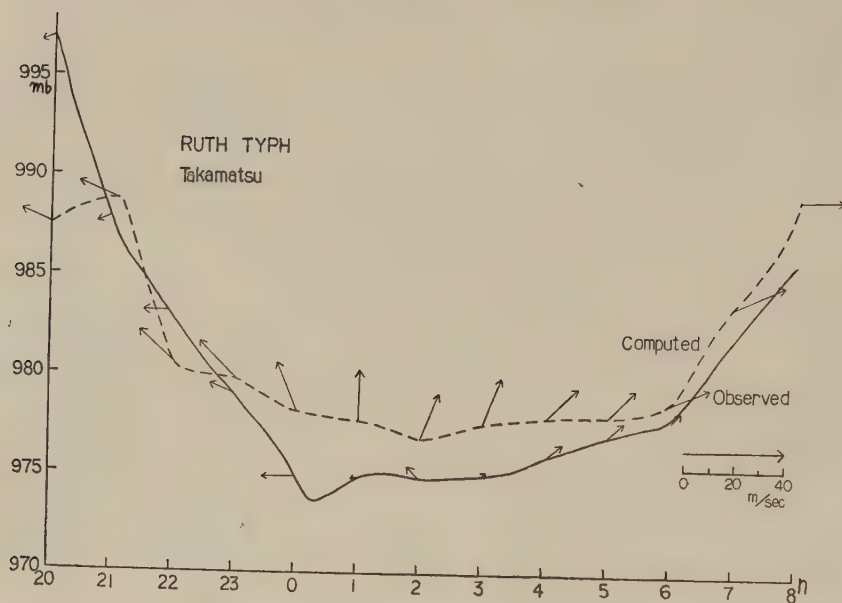


Fig. 16 (c, d). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. Ruth typhoon.

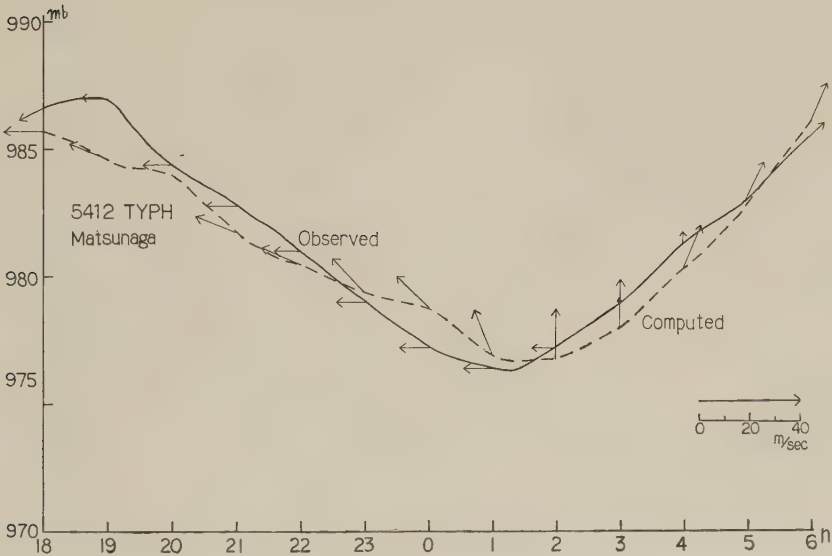
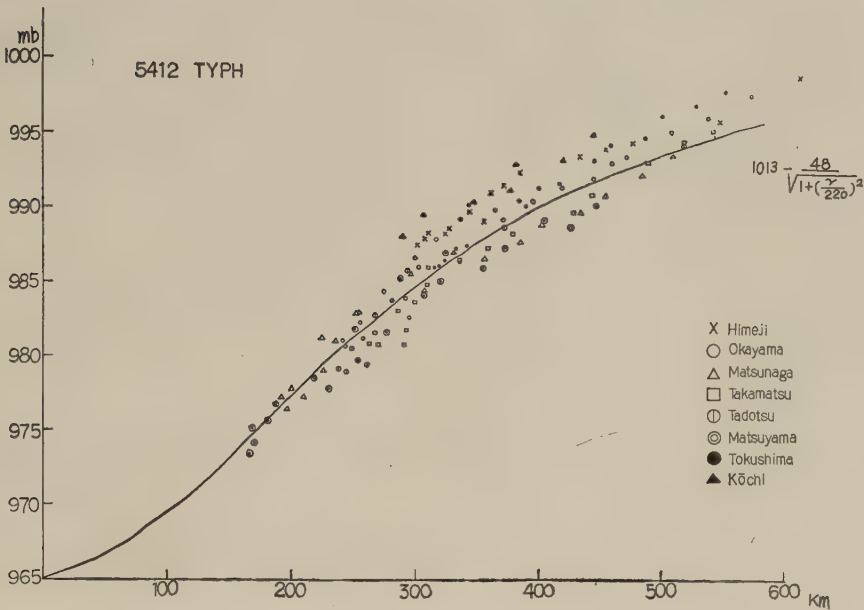


Fig. 17 (a, b). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. 5412 typhoon.

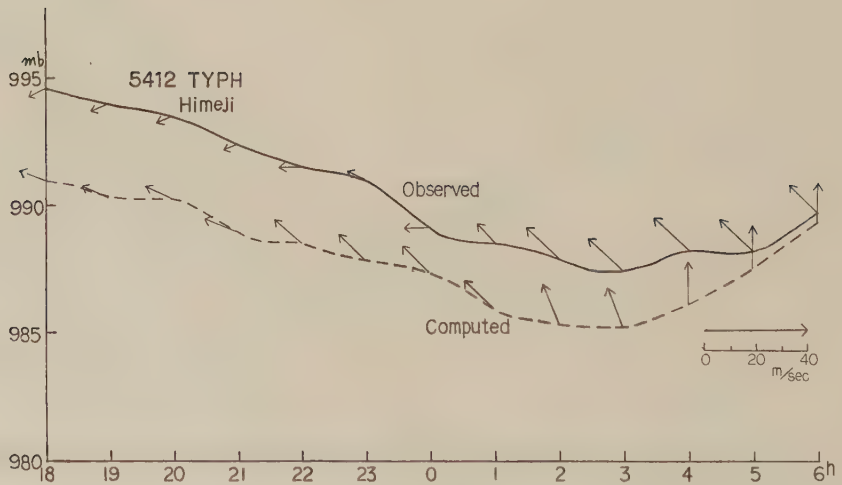
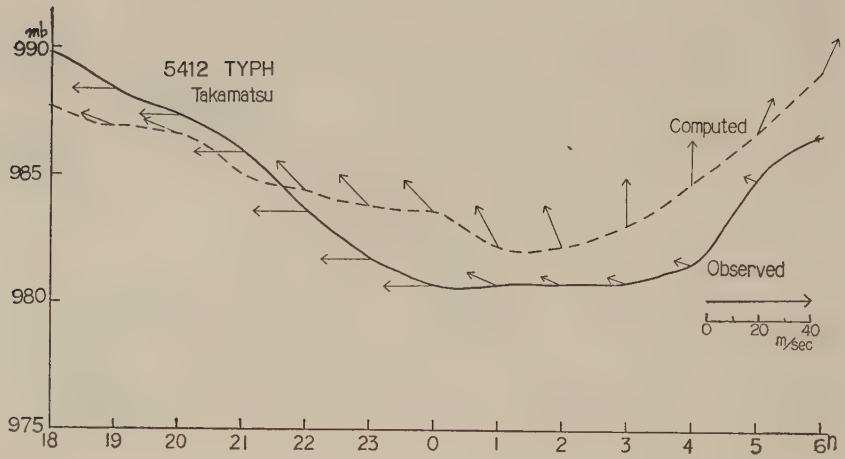


Fig. 17 (c, d). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. 5412 typhoon.

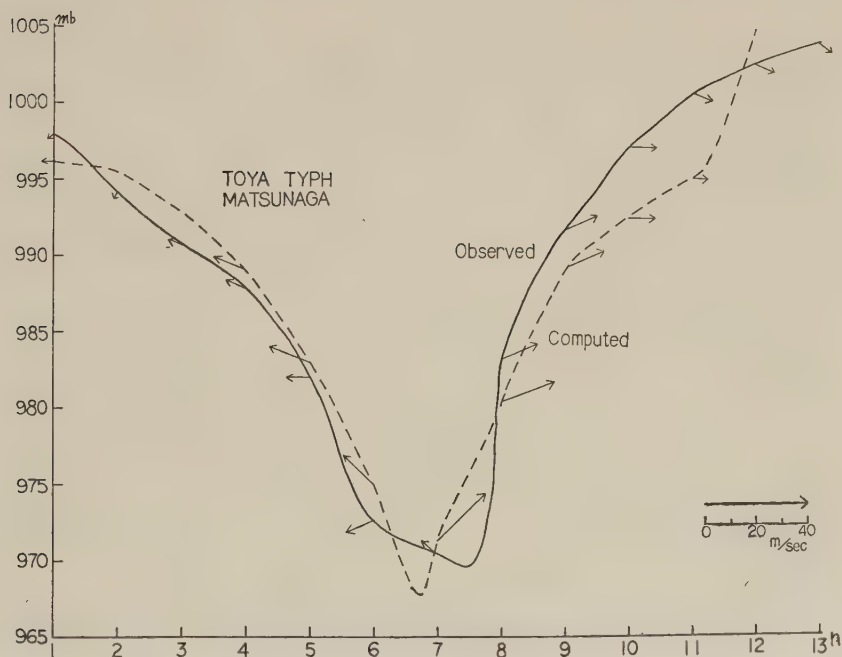
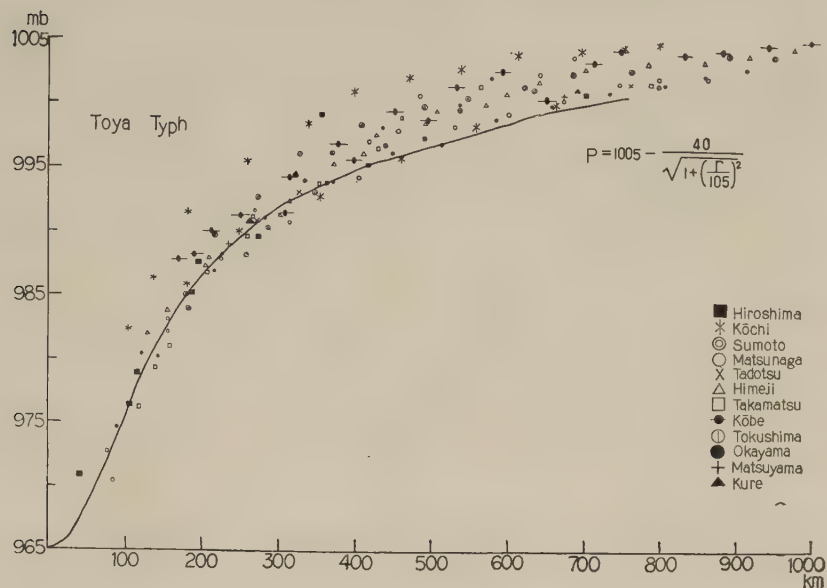


Fig. 18 (a, b). The comparison between observed and computed weather element, [Cf. Sec. 6.2]. Toya-maru typhoon.

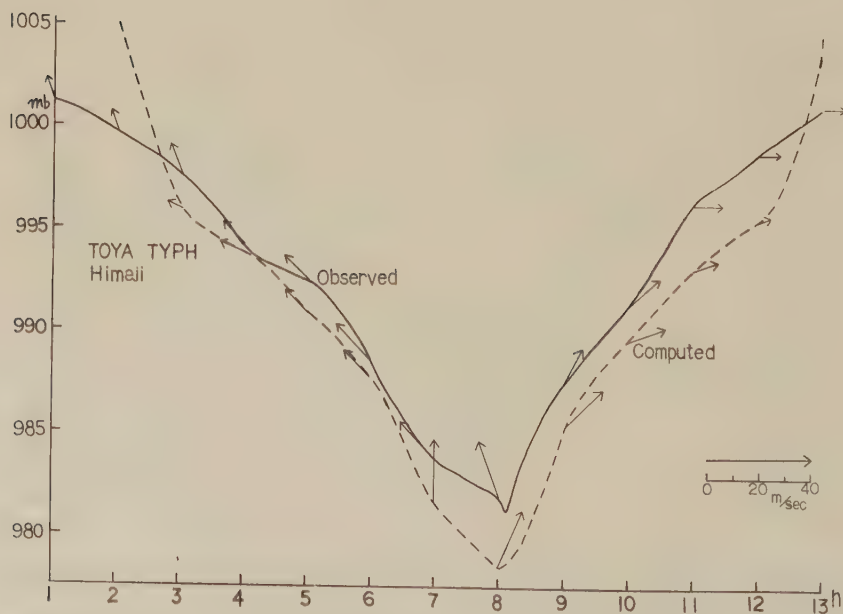
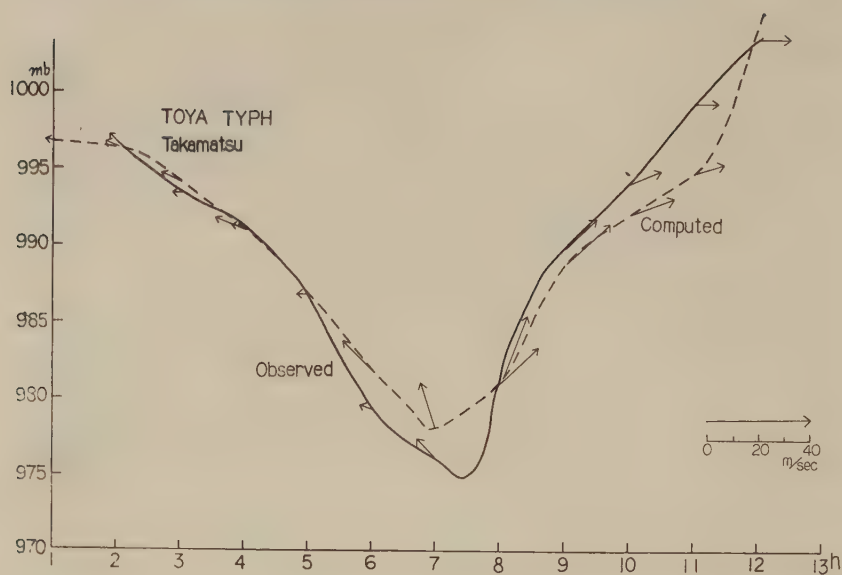


Fig. 18 (c, d). The comparison between observed and computed weather element. [Cf. Sec. 6.2]. Toya-maru typhoon.

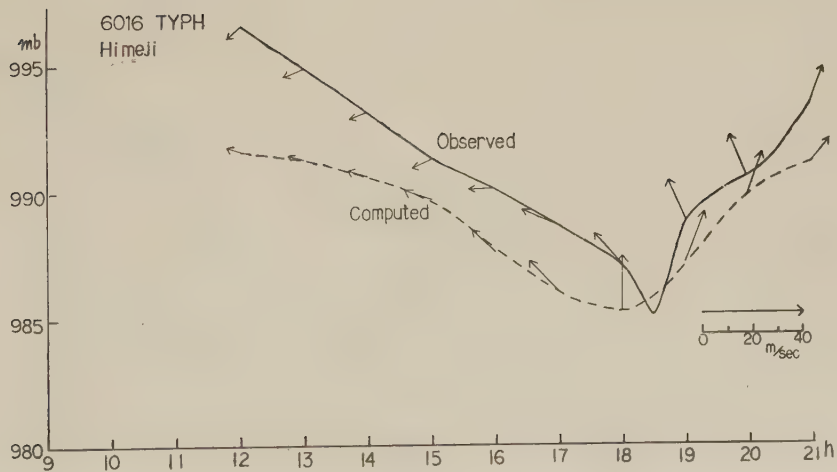
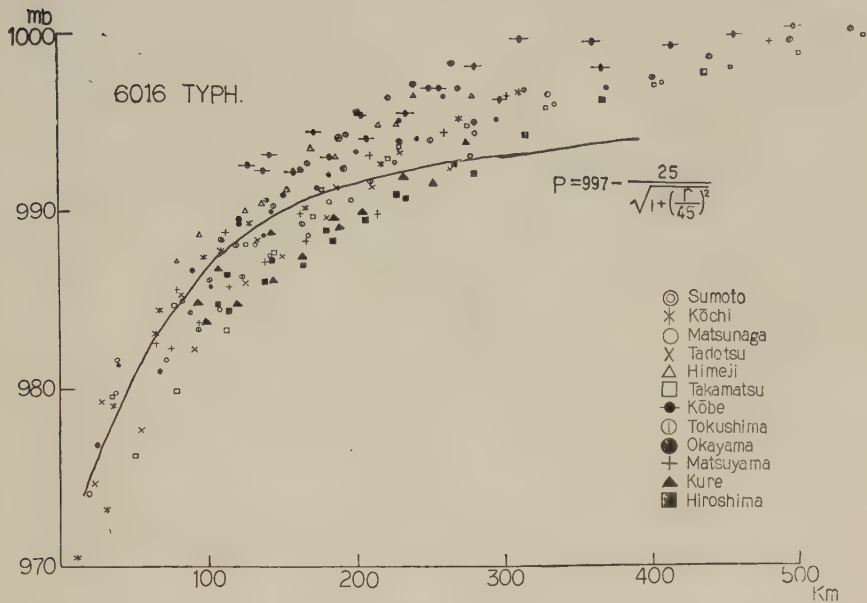


Fig. 19 (a, b). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. 6016 typhoon.

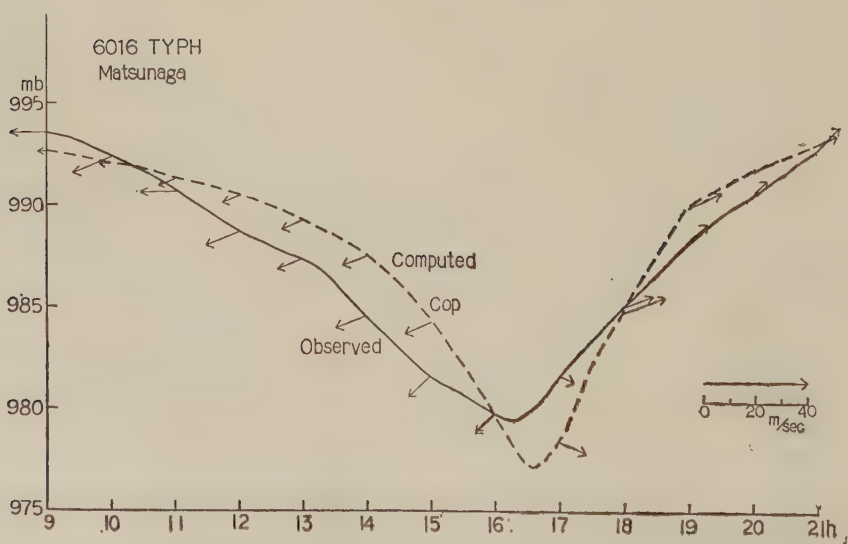
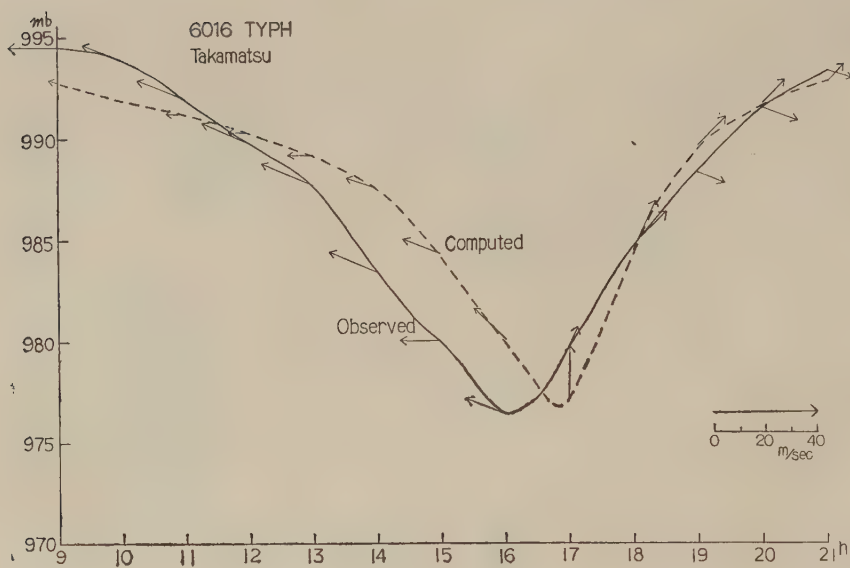


Fig. 19 (c, d). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. 6016 typhoon.

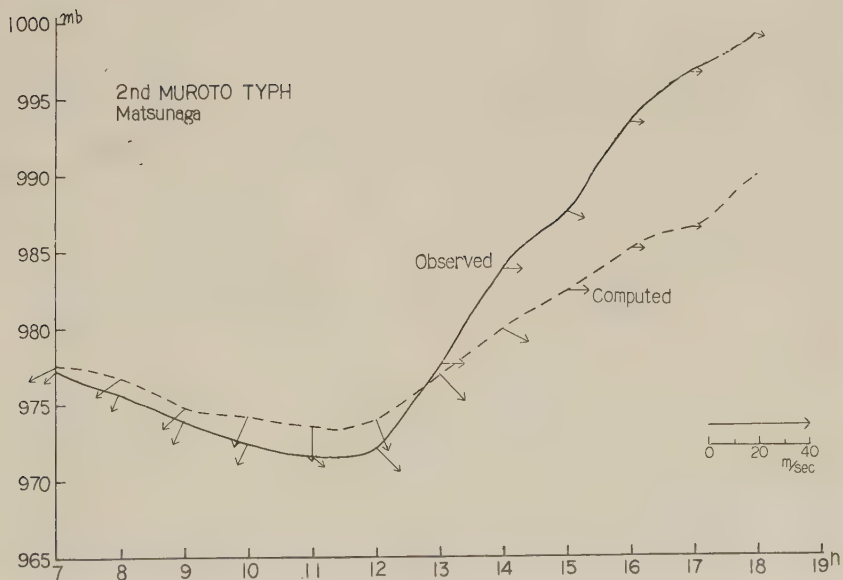
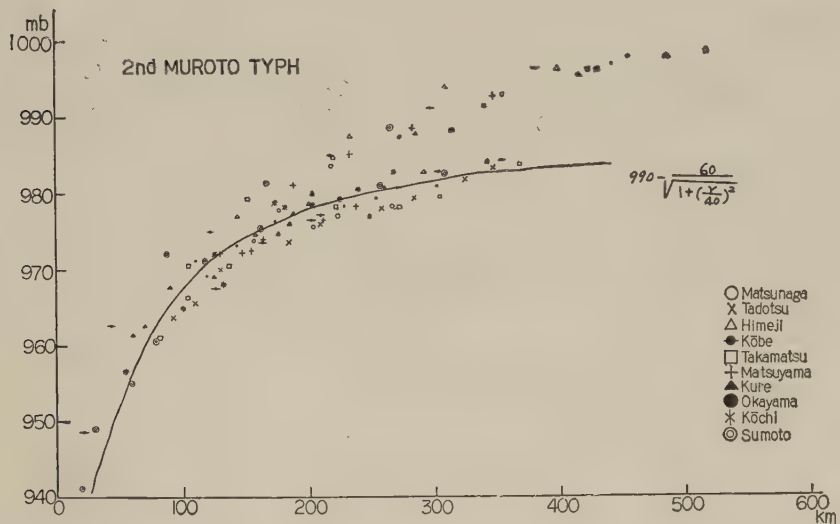


Fig. 20 (a, b). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. 2nd Muroto typhoon.

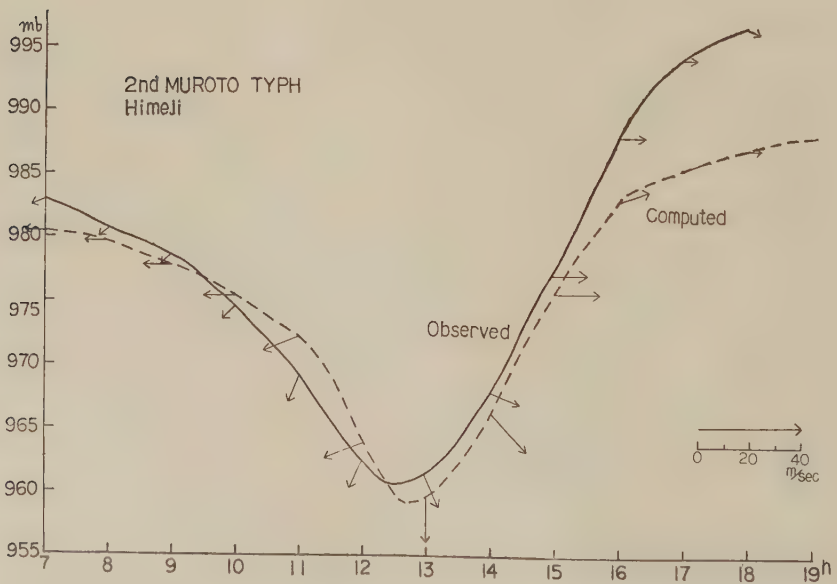
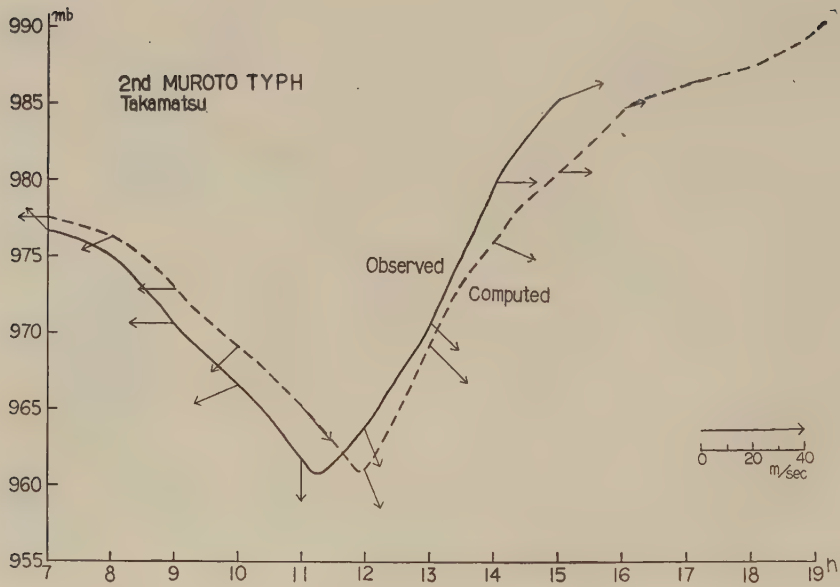


Fig. 20 (c, d). The comparison between observed and computed weather element.
[Cf. Sec. 6.2]. 2nd Muroto typhoon.

T. Ueno: Non-Linear Numerical Studies on Tides and Surges of Inland Sea

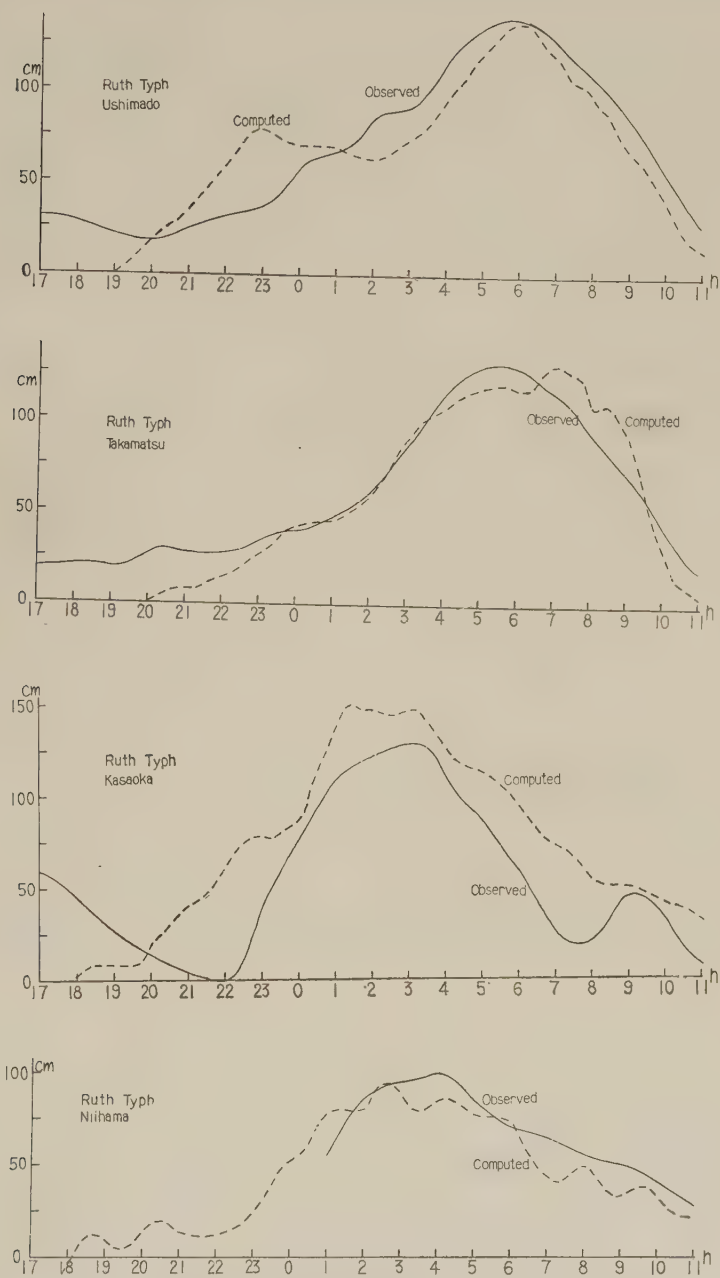


Fig. 21 (a, b, c, d). The comparison between observed and computed surges.
[Cf. Sec. 6.3]. Ruth typhoon.

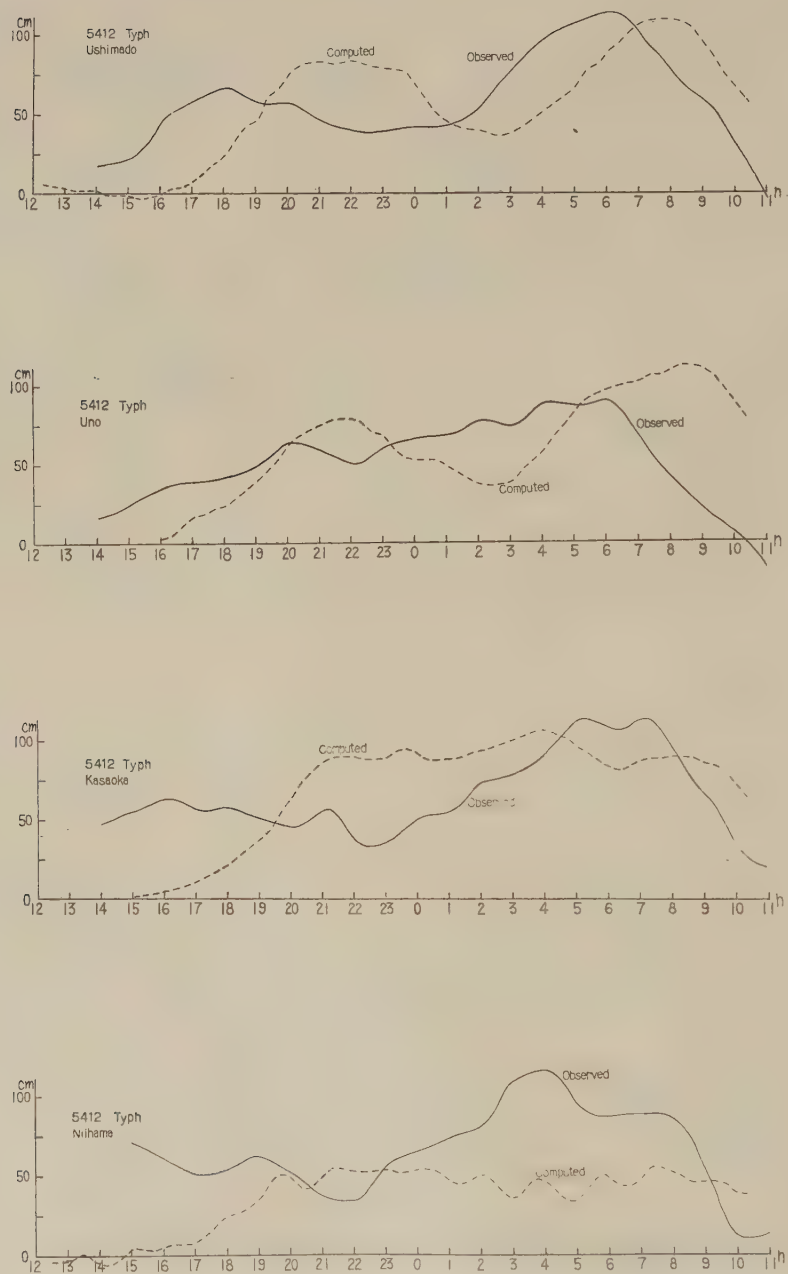


Fig. 22 (a, b, c, d). The comparison between observed and computed surges. [Cf. Sec. 6.3]. 5412 typhoon.

T. Ueno: Non-Linear Numerical Studies on Tides and Surges of Inland Sea

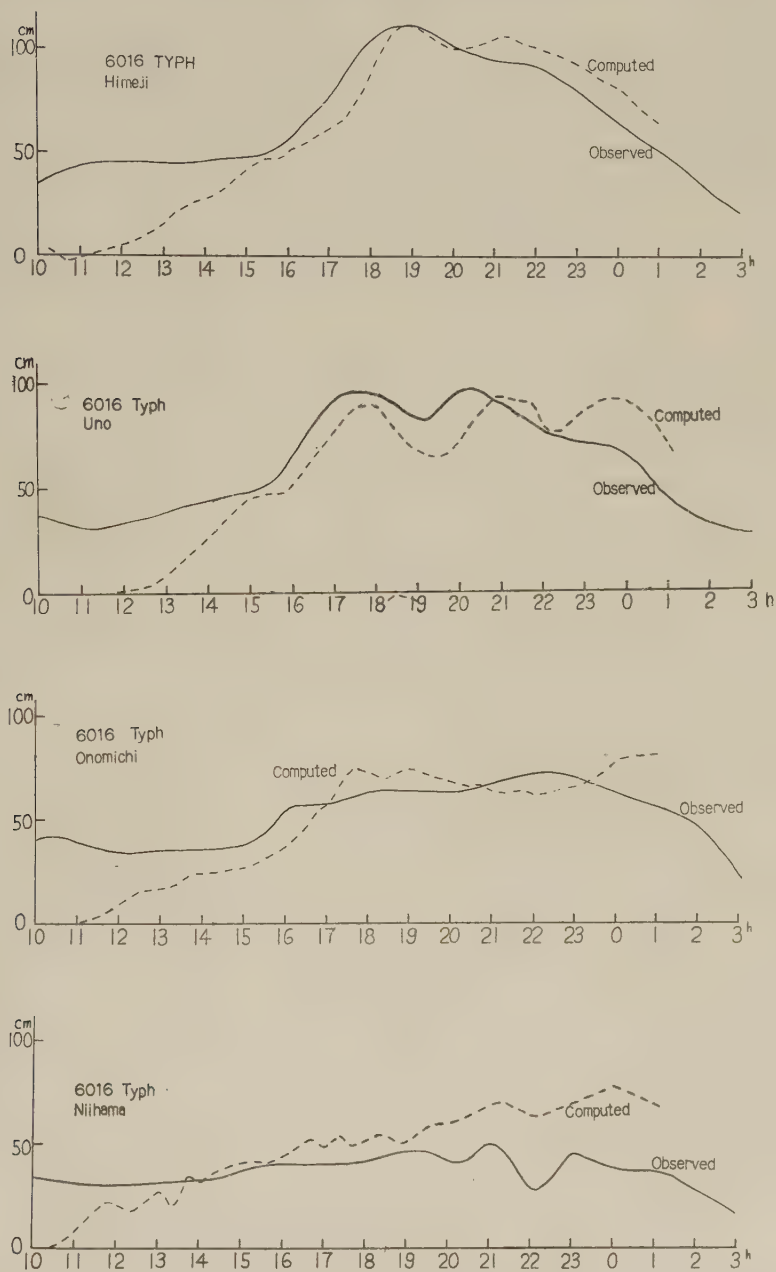


Fig. 23 (a, b, c, d). The comparison between observed and computed surges. [Cf. Sec. 6.3]. 6016 typhoon.

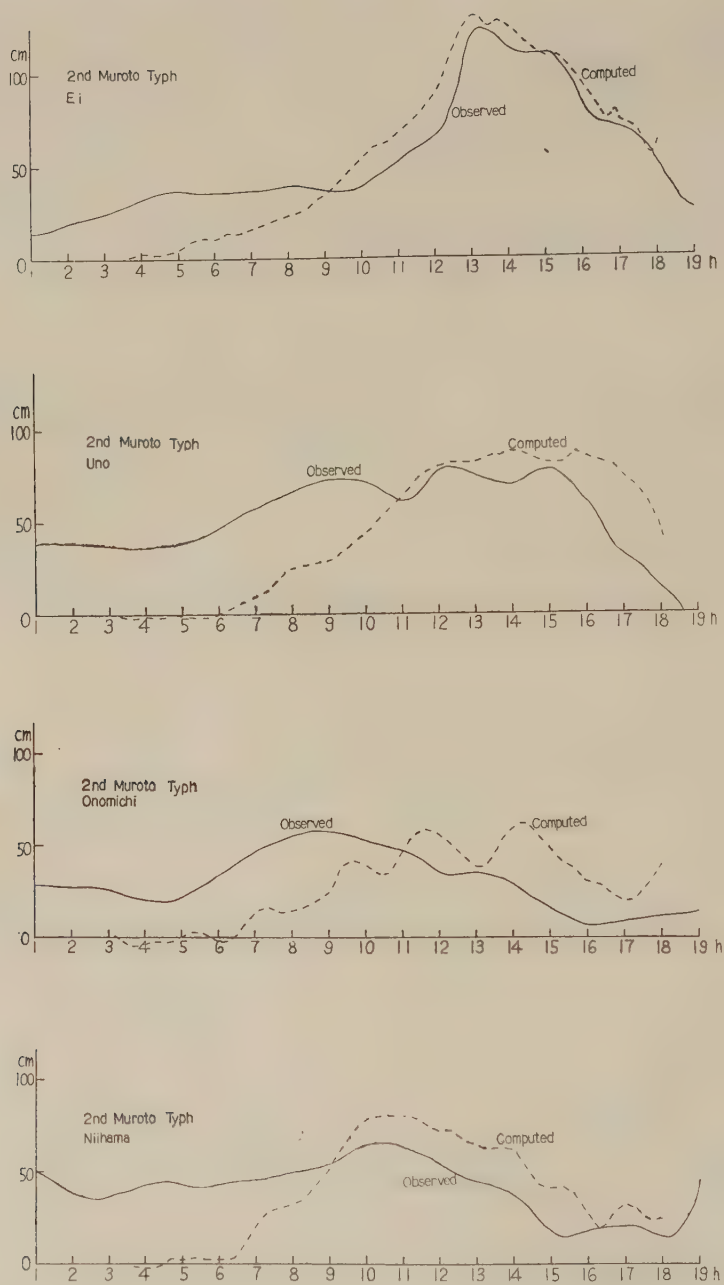


Fig. 24 (a, b, c, d). The comparison between observed and computed surges.
[Cf. Sec. 6.3] 2nd Muroto typhoon.

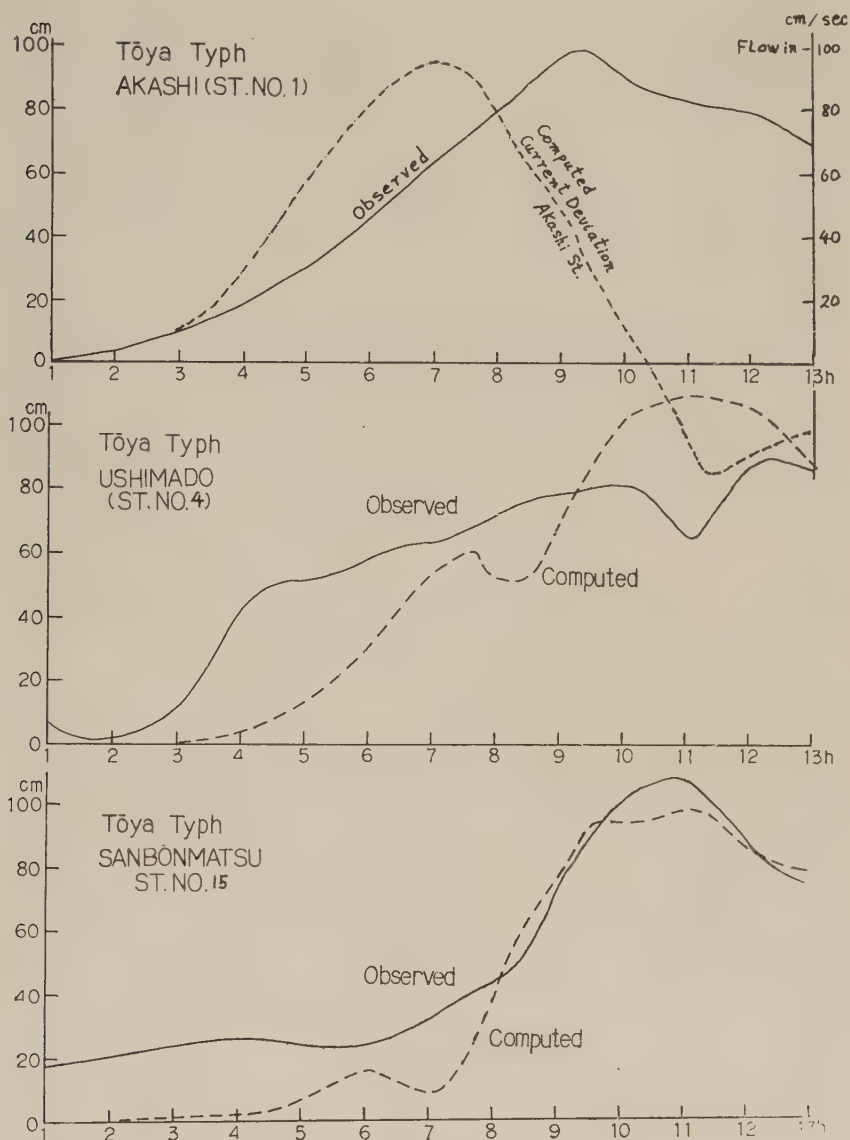


Fig. 25 (a, b, c). The comparison between observed and computed surges, [Cf. Sec. 6.4]. Toya-maru typhoon.

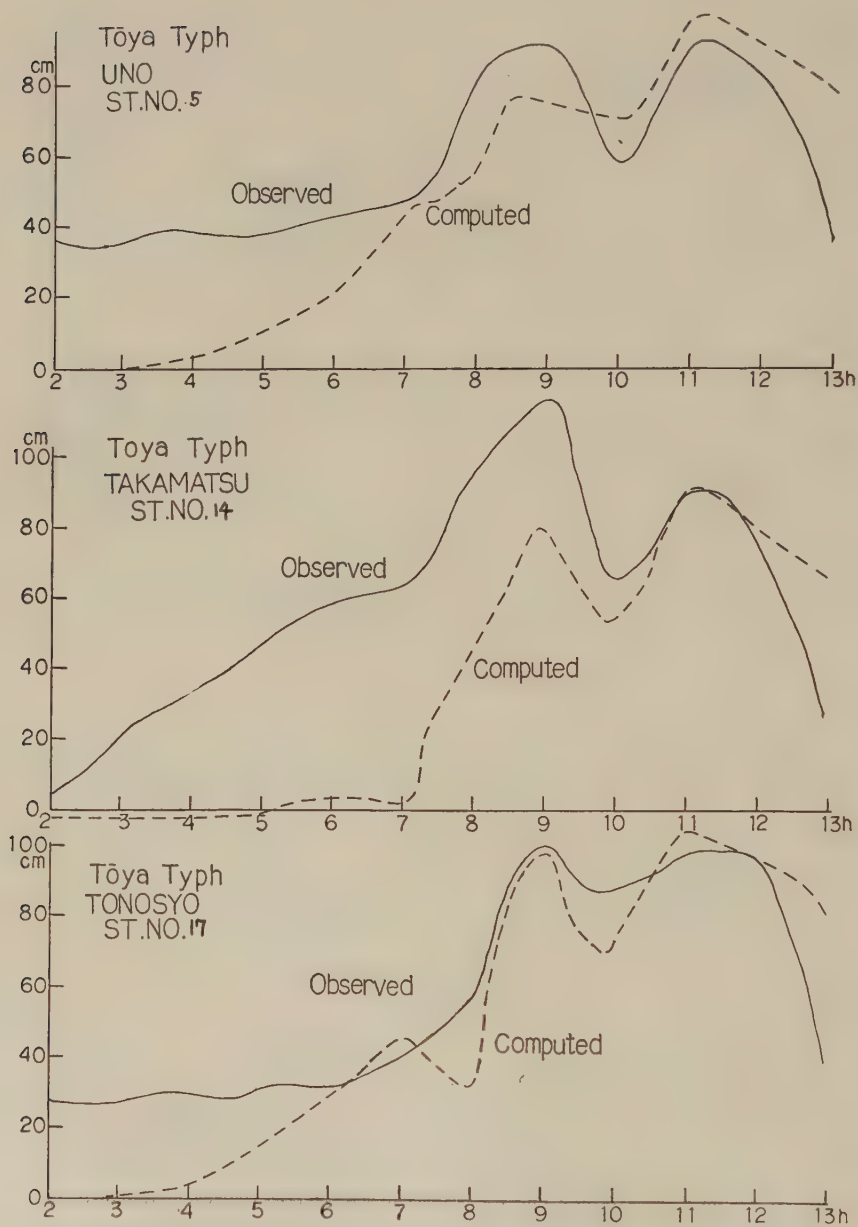


Fig. 25 (d, e, f). The comparison between observed and computed surges.
[Cf. Sec. 6.4]. Toya-maru typhoon.

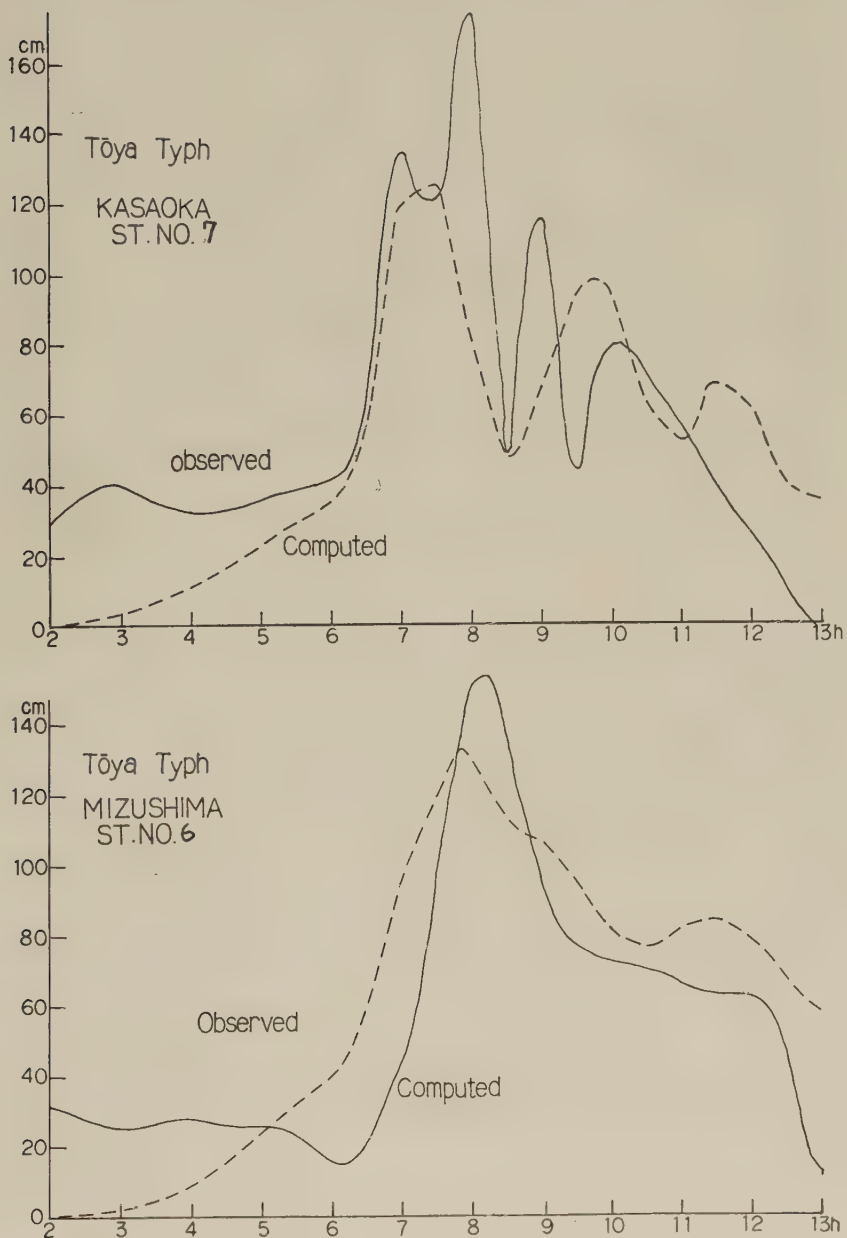


Fig. 25 (g, h). The comparison between observed and computed surges.
 [Cf. Sec. 6.4]. Tōya-maru typhoon.

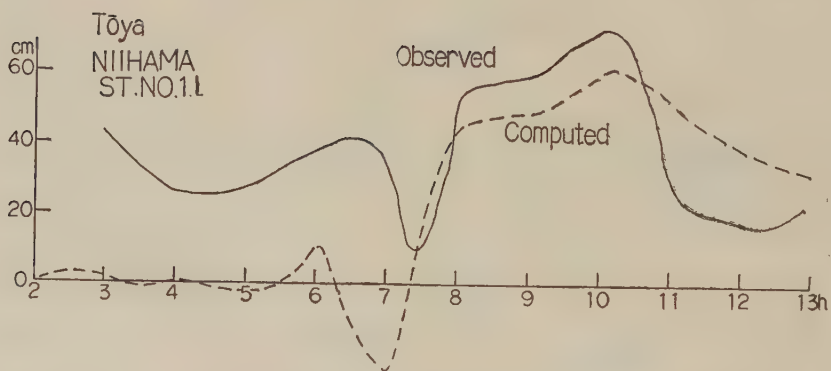
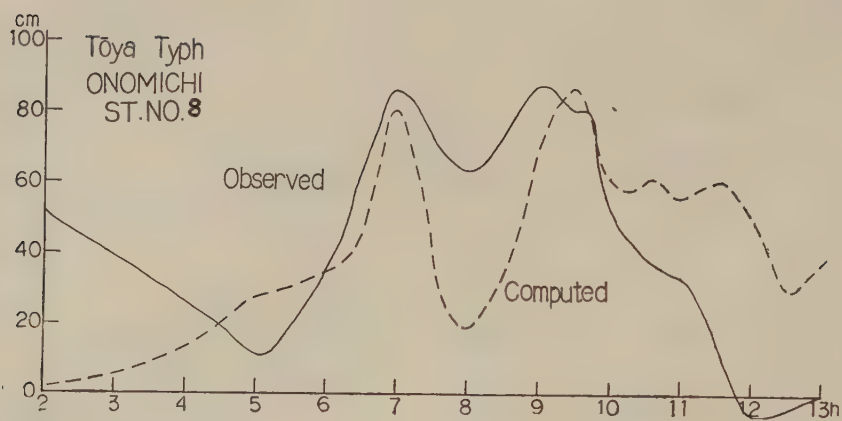


Fig. 25 (i, j). The comparison between observed and computed surges.
[Cf. Sec. 6.4]. Tōya-maru typhoon.

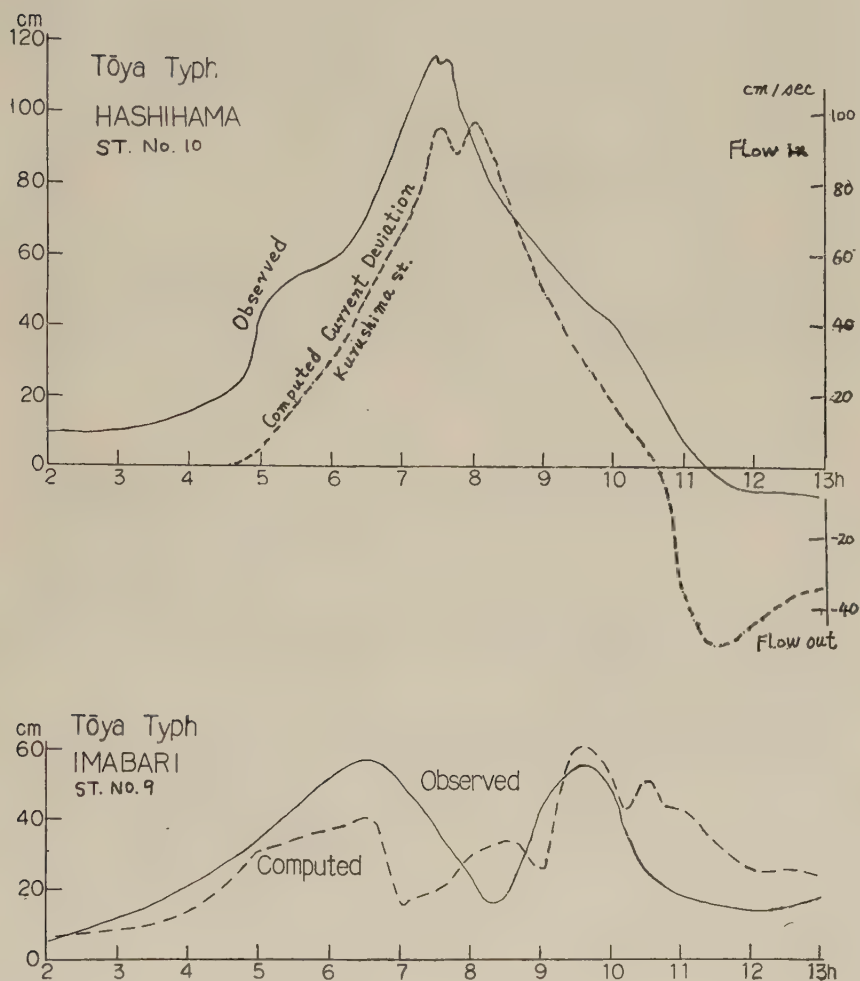


Fig. 25 (k, l). The comparison between observed and computed surges.
 [Cf. Sec. 6.4]. Toya-maru typhoon.

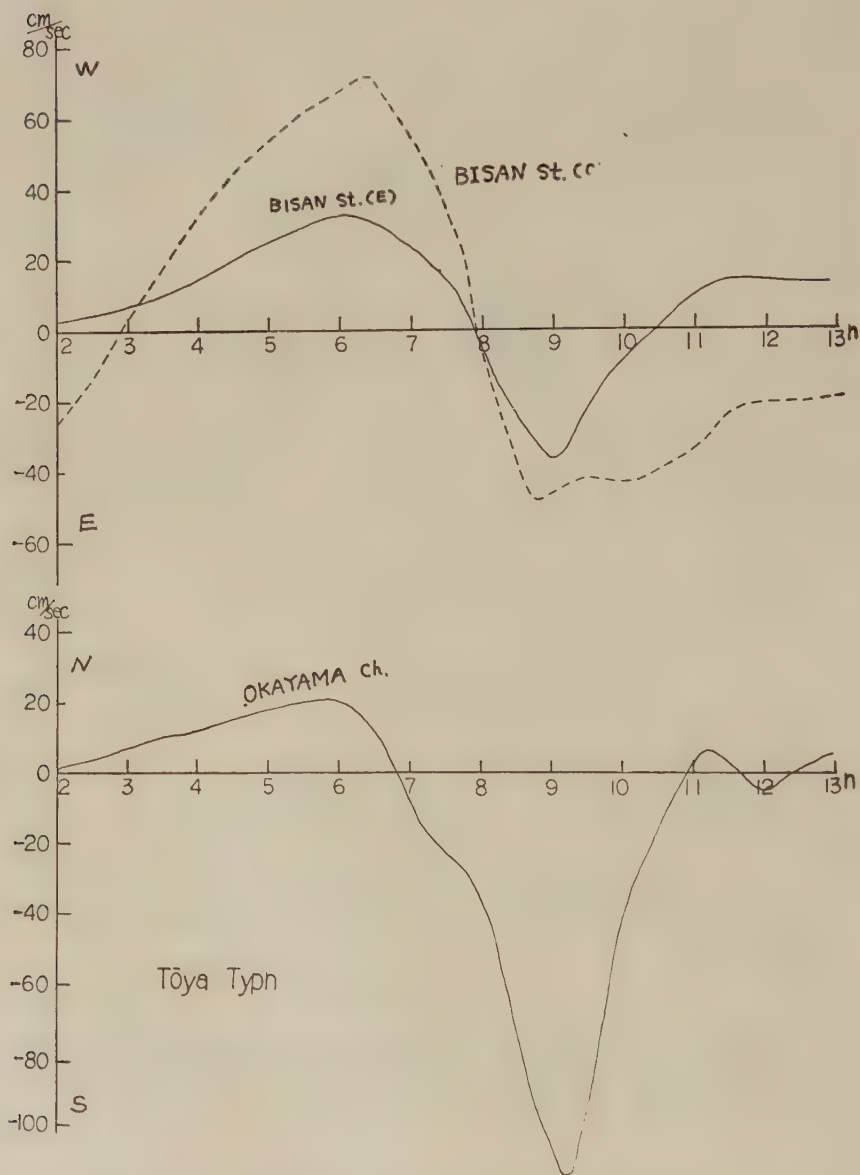


Fig. 25 (m, n). The computed velocity of surge current near Bisan Straits and Okayama Ch. [Cf. Sec. 6.4]. Toya-mar typhoon.

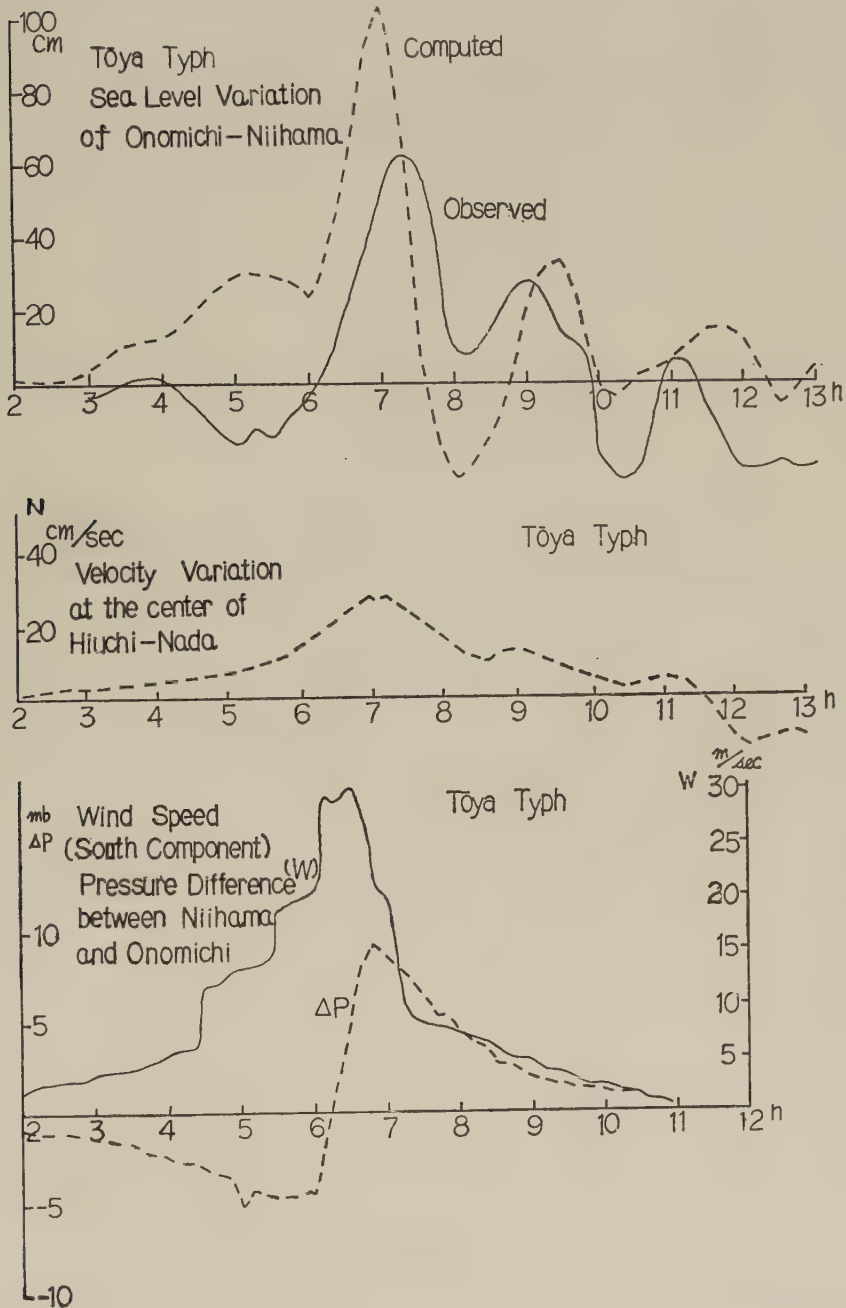


Fig. 25 (o, p, q). The seiches in Hiuchiⁱ Sea and its weather condition.
[Cf. Sec. 6.4]. Toya-maru typhoon.

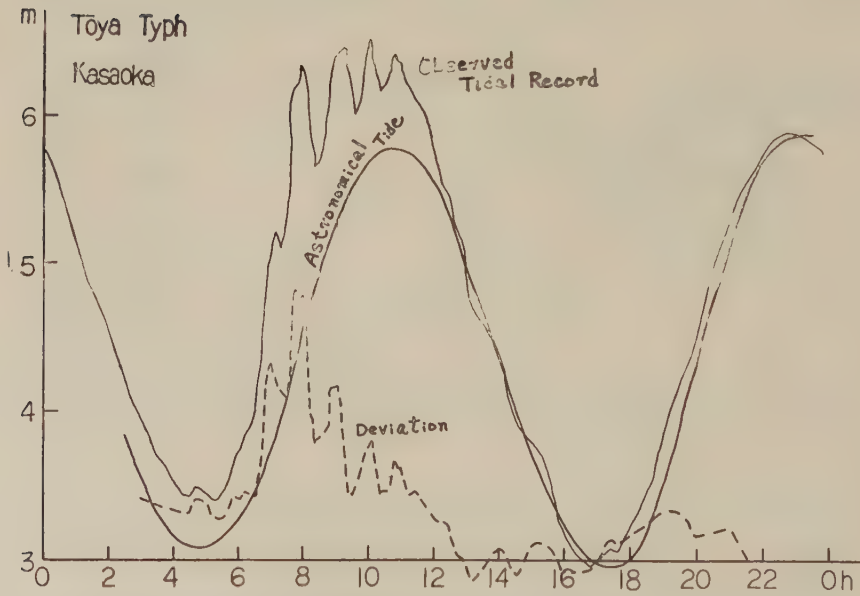
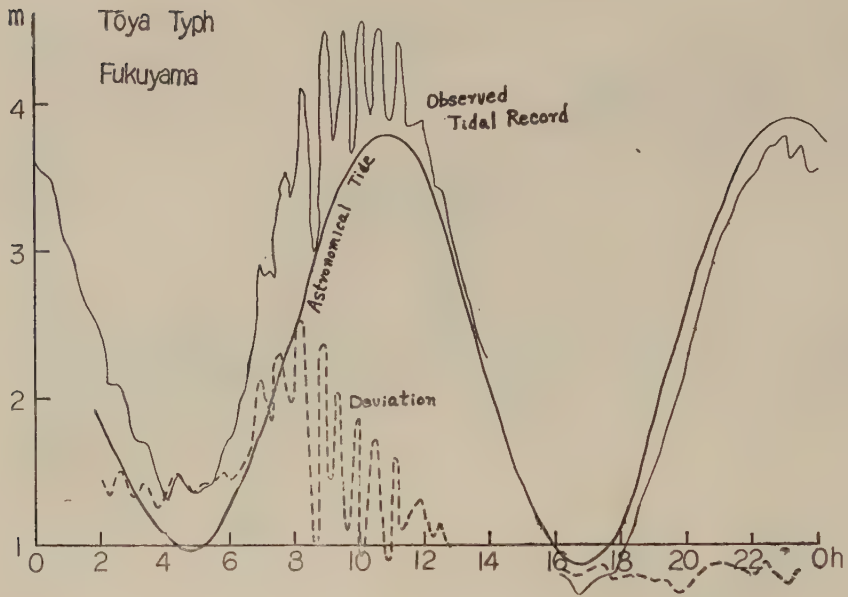


Fig. 25 (r, s). The example of tidal record at Toya-maru typhoon. [Cf. Sec. 6.4].

Preliminary Report of the Japanese Expedition of Deep-Sea, the Eighth Cruise, 1964 (JEDS-8)*

By

Hiroshi KATSUURA

Hideo AKAMATSU

Tsutomu AKIYAMA

Japan Meteorological Agency

(Received Dec. 12, 1964)

1. Introduction

The Japanese Expedition of Deep-Sea, the Eighth Cruise (JEDS-8) which was planned by the Deep-Sea Research Committee (Chairman, K. WADATI), Japan Society for Promotion of Science, was carried out from April 20th to May 6th, and from May 9th to 31st, 1964 on board the R/S Ryofu Maru (Captain, T. SUENAGA) of the Japan Meteorological Agency. The research stations were occupied at the

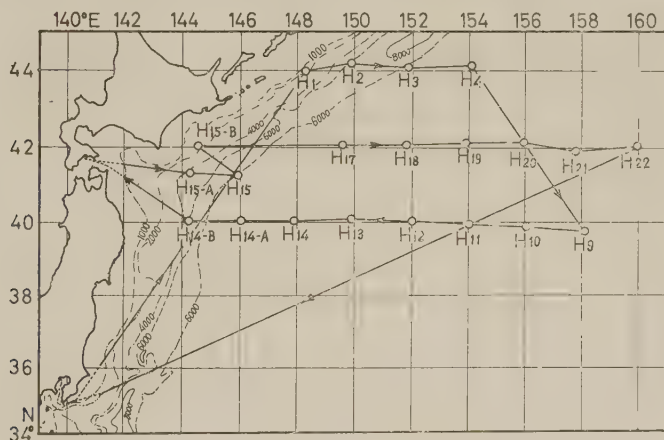


Fig. 1. The observational stations occupied by the Ryofu Maru in the Japanese Expedition of Deep-Sea, the Eighth Cruise (JEDS-8) in April to May, 1964.

* JEDS Contribution No. 59

neighbourhood of the southern part of the Kurile Trench and the northern part of the Japan Trench. In the former period, the project aimed mainly to hydrographical researches of the deep-current pattern in this area, and a few samplings of bottom sediment, chemical, geophysical, geological observations and so on were also carried out. In the later period, the original plan drew up various kinds of geophysical, geological, chemical observations or samplings with the deep-sea winch. But, during the dredgeing at St. H_{15-A}, the deep-sea wire was cut off by an accident and, since then, the observations or samplings were compelled to be carried out with the other 15 KW deep-sea winch and the gravity corer instead of the piston corer.

2. *The research members on board the Ryofu Maru*

April 20-May 6

Japan Meteorological Agency: H. KATSUURA (Phys. Ocean.), H. AKAMATSU (Phys. Ocean.), T. SAWARA (Phys. Ocean.), T. NAKAI (Phys. Ocean.), I. FUJIWARA (Phys. Ocean.), T. URASHIMA (Phys. Ocean.), T. AKIYAMA (Chemistry), K. YOSHIMURA (Chemistry), T. YURA (Chemistry), Y. KAWARADA (Plankton), K. FURUHASHI (Plankton)

Meteorological Research Institute: Y. SUGIMURA (Chemistry)

Hydrographic Office: Y. IWABUTI (Geology)

Tokyo University: S. UYEDA (Geophys.), T. WATANABE (Geophys.), M. KIMURA (Geology)

Tokyo University of Education: S. TAKEMATSU (Chemistry)

May 9-31

Japan Meteorological Agency: H. KATSUURA, H. AKAMATSU, T. SAWARA, T. NAKAI, I. FUJIWARA, T. URASHIMA, T. AKIYAMA, T. YURA, Y. KAWARADA, K. FURUHASHI

Meteorological Research Institute: Y. SUGIMURA

Tokyo University: T. WATANABE, K. KAWADA (Geophys.), Y. HAGIWARA (Geophys.), H. KAGAMI (Geology)

Kyushu University: H. MITSUSHIO (Geology)

Yamagata University: O. YAMAGATA (Geology)

Physical & Chemical Research Institute: G. OSHIBA (Phys. Ocean.), M. KISHINO (Phys. Ocean.)

3. *The items of observations or samplings*

- (1) Hydrographical cast from surface to bottom:
18 stations (H_1 — H_4 , H_9 — H_{14} , H_{14-A} , H_{14-B} , H_{17} — H_{22})
- (2) Water sampling for special analysis:
9 stations (H_2 , H_4 , H_9 , H_{11} , H_{13} , H_{14-A} , H_{14-B} , H_{19} , H_{22})
- (3) Measurement of geothermal gradient:
3 stations (H_{11} , H_{12} , H_{14-A})
- (4) Bottom-core sampling:
8 stations (H_{11} , H_{12} , H_{14-A} , H_{15-A} , H_{15-B} , H_{20} , H_{21} , H_{22})
- (5) Sampling of deep-water plankton: H_{20}
- (6) Measurement of bottom current: H_{15-B}
- (7) Measurement of γ -ray activity: H_{20}

Besides, the surface current measurements with GEK, BT observations, echo sounding and geomagnetic measurements were carried out underway.

4. *Results of the hydrographic cast*

Eighteen hydrographic stations were occupied between 40° N and 44° N latitude. In order to do exactly the geostrophic computation and the analysis of water properties especially in the deep water, the level of observation was taken at intervals of 250 m, in the layers from 1000 m to 4000 m, and 500 m below 4000 m.

The temperature measurement was made very carefully with the thermometer which was calibrated repeatedly. The salinity (chrolinity) was measured by the inductive salinometer (Auto-Lab.) and by using the thermostat for pre-warming the samples. On the other hand, the analyses of the nutrient salts were done by using the standard ampoule solutions in each station and were made more accurately.

5. *Results of the other branches*

Details of results in each branch shall be published in near future by other members and shall be collected in the "Report of JEDS" published by the Deep Sea Research Committee, Japan Society for Promotion of Science.

Table 1. Results of serial observations in JEDS-8, April-May 1964

St. H₁ (Ry 1978). 43°59'N, 148°20'E. April 24, 1964. Depth-2505m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	1.4	18.307	8.30	1.50	34	8.17	—	—
54	1.20	.312	7.90	1.60	28	.17	—	—
108	1.69	.443	5.58	2.17	48	.01	—	—
161	2.09	.533	4.44	2.35	59	7.93	—	—
214	2.26	.588	3.76	2.49	63	.90	—	—
319	2.82	18.692	2.38	2.67	89	7.80	—	—
421	3.04	.786	1.34	2.88	88	.70	—	—
524	3.21	.858	0.86	2.76	97	.67	—	—
627	3.16	.889	0.79	2.92	102	.66	—	—
835	2.66	.931	1.08	2.82	116	.71	—	—
1014	2.44	19.003	1.16	2.82	119	7.68	—	—
1042	2.44	18.998	1.14	2.92	116	.73	—	—
1227	2.33	19.056	1.20	2.92	124	.69	—	—
1447	2.25	.081	1.31	2.96	124	.73	—	—
1674	2.19	.109	1.39	2.92	131	.74	—	—
2136	1.86	19.156	2.15	2.76	131	7.83	—	—

St. H₂ (Ry 1979). 44°08'N, 149°58'E. April 24~25, 1964. Depth-6440m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	1.9	18.311	8.16	1.36	34	8.11	0.31	—
52	1.70	.316	7.92	1.46	35	.09	0.34	—
104	1.53	.343	7.47	1.65	38	.10	0.36	—
152	1.68	.418	6.38	1.82	46	.03	0.10	—
201	2.80	.575	4.02	2.10	62	7.88	0.05	—
297	3.00	18.711	2.20	2.60	78	7.72	0.05	—
393	3.22	.808	1.48	2.68	88	.67	tr	—
491	3.34	.887	1.28	2.74	98	.68	tr	—
592	3.09	.918	0.91	2.76	108	.66	0.00	—
800	2.92	.981	0.90	2.70	117	.69	0.00	—
1013	2.62	19.030	0.95	2.79	123	7.70	—	—
1296	2.38	.079	1.16	2.71	123	.75	—	—
1461	2.22	.100	1.29	2.76	135	.74	—	—
1653	2.14	.118	1.40	2.81	135	.76	—	—
1846	2.06	.138	1.63	2.74	135	.81	—	—
2248	1.85	19.161	2.13	2.50	130	7.84	—	—
2665	1.70	.179	2.61	2.44	136	.90	—	—
2878	1.62	.188	3.13	2.42	133	.93	—	—
3656	1.50	.198	3.49	2.17	127	.94	—	—
3899	1.48	.200	3.53	2.44	127	.93	—	—
4143	1.49	19.201	3.63	2.36	125	7.93	—	—
4635	1.50	.203	3.74	2.30	125	.92	—	—
5130	1.56	.204	3.76	2.20	123	.92	—	—

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St. H₃ (Ry 1980). 44°04'N, 152°00'E. April 25~26, 1964. Depth-5470m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	1.9	18.271	8.11	2.05	27	8.09	—	—
55	1.34	.275	7.88	2.02	26	.11	—	—
109	1.57	.279	6.07	2.54	34	.07	—	—
164	3.20	.670	1.84	3.23	63	7.68	—	—
218	3.39	.762	0.80	3.38	63	.61	—	—
327	3.43	18.846	0.54	3.17	54	7.61	—	—
436	3.38	.915	0.43	3.30	79	.62	—	—
545	3.22	.956	0.41	3.38	96	.62	—	—
655	2.74	.966	—	3.00	91	.66	—	—
873	2.55	19.023	0.96	3.19	102	.70	—	—
1091	2.35	19.064	1.02	3.30	106	7.70	—	—
1364	2.27	.107	1.13	2.99	119	.69	—	—
1507	2.18	.124	1.33	3.26	110	.70	—	—
1752	2.05	.146	1.59	3.23	95	.71	—	—
1998	1.90	.161	1.94	3.24	86	.77	—	—
2492	1.68	19.180	2.49	2.90	99	7.89	—	—
2988	1.57	.194	3.00	2.90	97	.84	—	—
3237	1.54	.197	3.28	2.76	80	.87	—	—
3486	1.51	.202	3.31	2.78	100	.86	—	—
3736	1.50	.203	3.44	2.75	103	.86	—	—
3986	1.48	19.205	3.50	2.64	79	7.86	—	—
4487	1.50	.208	3.62	3.09	116	.86	—	—
4988	1.54	.209	3.70	2.74	101	.85	—	—

St. H₄ (Ry 1981). 44°06'N, 154°04'E. April 26, 1964. Depth-5140m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	2.6	18.300	8.11	1.68	34	8.10	0.40	—
51	2.14	.301	7.74	1.50	34	.10	0.41	—
100	1.70	.309	7.38	1.60	36	.10	0.43	—
149	1.64	.393	6.44	1.76	46	.01	0.17	—
196	3.02	.617	2.62	2.35	75	7.72	0.01	—
285	3.57	18.791	0.72	2.76	90	7.62	0.00	—
373	3.31	.851	0.70	2.68	94	—	0.00	—
460	3.22	.895	0.74	2.98	111	7.62	0.00	—
548	3.08	.934	0.65	2.78	111	.62	0.00	—
729	2.91	.993	0.54	2.74	129	.62	0.00	—
900	2.64	19.040	0.84	2.87	126	7.67	—	—
919	2.66	.037	0.76	2.60	134	.64	—	—
1016	2.59	.068	0.91	2.70	134	.66	—	—
1131	2.46	.084	1.06	2.70	126	.70	—	—
1187	2.46	.085	0.97	2.60	141	.68	—	—
1356	2.25	19.105	1.21	2.70	134	7.71	—	—
1586	2.13	.128	1.33	2.80	146	.73	—	—
1700	2.04	.140	1.56	2.95	141	.73	—	—

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St. H₉ (Ry 1982). 39°43'N, 158°08'E. April 28~29, 1964. Depth-5515m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	11.0	18.945	6.71	0.53	16	8.19	0.17	—
54	9.18	.889	6.33	0.59	20	.16	0.25	—
110	7.81	.830	6.28	0.67	21	.14	0.26	—
163	7.32	.805	6.52	0.90	20	.14	tr	—
217	7.14	.798	6.52	0.85	22	.15	tr	—
324	7.00	18.790	6.48	1.01	23	8.13	tr	—
430	5.07	.759	3.66	1.83	51	7.90	0.00	—
537	4.25	.812	2.46	2.53	88	.78	0.00	—
646	3.90	.861	1.72	2.77	75	.72	0.00	—
865	3.36	.960	1.04	3.12	112	.69	0.00	—
1089	2.86	19.023	0.90	2.97	114	7.68	—	—
1376	2.44	.077	1.01	2.88	140	.69	—	—
1482	2.34	.094	1.09	3.03	136	.69	—	—
1703	2.17	.115	1.29	3.10	136	.70	—	—
2384	1.68	.173	2.62	2.67	136	.78	—	—
2850	1.63	19.178	2.75	2.63	131	7.83	—	—
3087	1.58	.184	3.13	2.55	131	.85	—	—
3326	1.52	.189	3.18	2.46	131	.85	—	—
3566	1.51	.191	3.29	2.53	134	.88	—	—
3806	1.50	.193	3.39	2.43	126	.87	—	—
4286	1.49	19.198	3.56	2.50	127	7.89	—	—
4772	1.53	.200	3.66	2.40	128	.90	—	—

St. H₁₀ (Ry 1983). 39°52'N, 155°59'E. April 29, 1964. Depth-5500m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	12.6	19.061	6.35	0.50	14	8.17	0.21	—
59	12.59	.080	6.17	0.55	14	.19	0.21	—
118	10.54	18.977	5.29	1.03	21	.14	tr	—
177	9.28	.926	6.15	1.02	17	.15	0.12	—
236	8.21	.863	6.08	1.03	21	.14	0.06	—
321	7.08	18.804	6.32	1.11	21	8.13	0.00	—
428	4.95	.771	3.49	2.16	45	7.87	0.00	—
534	4.38	.844	2.21	2.69	52	.87	0.00	—
641	4.03	.905	1.62	2.76	65	.69	0.00	—
859	3.27	.988	0.99	2.97	97	.67	0.00	—
1079	2.70	19.047	0.89	2.98	112	7.67	—	—
1362	2.27	.096	1.12	2.97	116	.70	—	—
1650	2.08	.096*	1.50	3.11	127	.72	—	—
1884	1.97	.126	1.72	2.97	121	.72	—	—
2112	1.94	.135	1.79	2.77	107	.75	—	—
2571	1.81	19.164	2.21	2.69	132	7.77	—	—
3033	1.62	.183	2.85	2.59	108	.84	—	—
3266	1.56	.187	3.16	2.60	72	.88	—	—
3501	1.54	.191	3.24	2.58	128	.87	—	—
3735	1.51	.193	3.34	2.49	126	.89	—	—
3970	1.48	19.196	3.49	2.69	75	7.90	—	—
4444	1.50	.198	3.60	2.61	82	.89	—	—
4930	1.53	.199	3.71	2.70	71	.89	—	—

* value doubtful

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St. H₁₁ (Ry 1984). 39°53'N, 153°58'E. April 30, 1964. Depth-5620m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	12.7	19.088	6.37	0.46	8	8.19	0.20	—
59	12.51	.070	6.06	0.53	9	.19	0.25	—
118	10.56	18.956	5.31	0.95	16	.14	0.05	—
177	9.10	.896	6.14	0.93	16	.15	0.19	—
236	7.92	.846	5.75	1.13	17	.12	tr	—
331	6.16	—	3.76	1.64	33	7.95	tr	—
445	4.59	18.832	2.63	2.21	42	.82	0.00	—
561	4.03	.880	1.78	2.48	74	.73	0.00	—
679	3.78	.936	1.34	2.63	68	.69	0.00	—
914	3.12	19.017	0.96	2.70	77	.67	0.00	—
1151	2.70	19.071	0.96	2.74	87	7.67	—	—
1449	2.38	.108	1.07	2.76	101	.71	—	—
1748	2.16	.129	1.39	2.76	65	.72	—	—
1885	2.00	.144	1.60	2.79	116	.73	—	—
2126	1.86	.159	1.97	2.78	98	.78	—	—
2610	1.65	19.177	2.64	2.50	86	7.82	—	—
3094	1.55	.189	3.04	2.39	80	.84	—	—
3337	1.52	.193	3.25	2.59	93	.87	—	—
3581	1.50	.197	3.35	2.50	78	.88	—	—
3825	1.50	.198	3.45	2.32	76	.90	—	—
4069	1.48	19.201	3.53	2.35	71	7.90	—	—
4558	1.51	.202	3.64	2.35	79	.89	—	—
5050	1.55	.203	3.74	2.28	76	.90	—	—

St. H₁₂ (Ry 1985). 40°03'N, 152°01'E. May 1, 1964. Depth-5460m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	13.7	19.132	6.25	0.26	14	8.25	—	—
50	11.84	.025	5.60	0.69	19	.21	—	—
100	10.68	18.969	5.18	0.91	24	.18	—	—
150	9.18	.890	5.08	1.10	23	.15	—	—
200	7.91	.835	4.35	1.43	36	.09	—	—
308	6.46	18.859	3.66	1.97	59	8.08	—	—
404	4.46	.827	2.92	2.33	68	7.88	—	—
500	4.48	.833	2.04	2.59	85	.82	—	—
597	4.09	.929	1.53	2.67	91	.77	—	—
792	3.40	.987	1.06	2.86	115	.73	—	—
988	2.94	19.041	0.95	2.99	124	7.71	—	—
1234	2.59	.078	0.96	2.87	134	.73	—	—
1481	2.34	.106	1.14	2.96	142	.73	—	—
1818	2.06	.132	1.55	2.95	148	.76	—	—
2067	1.90	.157	1.89	2.83	119	.80	—	—
2566	1.68	19.176	2.56	2.71	145	7.84	—	—
3066	1.57	.188	2.97	2.59	121	.87	—	—
3315	1.53	.192	3.24	2.57	137	.91	—	—
3568	1.51	.193	3.30	2.53	133	.90	—	—
3820	1.50	.198	3.40	2.49	133	.89	—	—
4072	1.50	19.200	3.50	2.59	134	7.90	—	—
4576	1.51	.203	3.65	2.61	129	.92	—	—
5079	1.56	.205	3.74	2.59	128	.91	—	—

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St. H₁₃ (Ry 1986). 40°02'N, 149°53'E. May 2, 1964. Depth-5675m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	8.4	18.698	7.29	0.90	15	8.15	0.27	7.8
50	7.26	.696	7.04	0.94	21	.13	0.25	6.2
100	5.87	.651	6.54	1.27	25	.09	0.36	9.0
150	4.66	.587	6.73	1.35	25	.08	0.05	15.4
200	4.11	.597	5.38	1.82	35	.08	0.00	18.4
315	2.84	18.656	3.26	2.33	53	7.79	0.00	13.0
405	3.17	.773	2.12	2.66	58	.70	0.00	15.2
515	3.45	.875	1.40	2.55	56	.66	0.00	9.6
630	3.30	.938	1.05	1.86	75	.65	0.00	8.5
840	2.99	19.005	0.93	2.71	85	.66	0.00	8.7
1050	2.66	.051	0.90	2.68	77	7.66	—	6.0
1310	2.42	.111	1.06	2.38	80	.66	—	8.5
1570	2.24	.123	1.27	2.81	87	.68	—	5.6
1807	2.05	.140	1.66	2.70	101	.71	—	—
2060	1.90	.150	2.18	2.74	92	.74	—	6.8
2564	1.66	19.176	2.64	2.63	101	7.80	—	4.0
3106	1.56	.186	3.11	2.55	93	.81	—	4.2
3358	1.53	.192	3.24	2.44	73	.84	—	—
3609	1.52	.195	3.33	2.31	73	.83	—	4.4
3860	1.50	.196	3.41	2.52	90	.85	—	—
4112	1.49	19.198	3.55	2.38	75	7.88	—	5.6
4615	1.51	.198	3.66	2.38	95	.89	—	4.6
5118	1.55	.199	3.77	2.47	108	.90	—	5.0

St. H₁₄ (Ry 1987). 40°01'N, 148°01'E. May 3, 1964. Depth-5320m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	7.6	18.533	7.63	0.84	14	8.23	—	—
47	3.11	.372	7.73	1.48	26	.13	—	—
98	2.44	.424	7.22	1.59	33	.10	—	—
152	2.64	.477	6.61	1.82	36	.06	—	—
206	2.71	.574	4.15	2.26	59	7.89	—	—
306	3.86	18.743	2.84	2.48	66	7.81	—	—
408	3.30	.813	1.76	2.71	83	.75	—	—
589	3.31	.939	1.06	3.18	101	.67	—	—
697	3.10	.973	0.97	2.94	107	.68	—	—
903	2.71	19.026	0.96	2.91	122	.68	—	—
1116	2.55	19.070	0.97	2.86	125	7.69	—	—
1382	2.29	.105	1.20	2.71	130	.72	—	—
1659	2.10	.131	1.45	2.71	134	.75	—	—

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St. H_{14-A} (Ry 1988). 40°01'N, 146°02'E. May 3~4, 1964. Depth-5150m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	5.7	18.342	8.09	1.21	14	8.07	0.29	10.0
50	2.52	.376	7.61	1.64	31	.09	0.40	17.0
100	2.30	.410	7.19	1.78	35	.06	0.34	15.2
150	2.36	.469	5.96	1.99	44	7.99	0.28	22.7
200	2.62	.568	3.86	2.63	60	.78	0.00	28.6
310	2.95	18.699	2.25	2.89	77	7.67	0.00	30.2
414	2.89	.786	1.77	2.97	88	.65	0.00	32.8
518	3.08	.867	1.21	3.01	100	.62	0.00	31.5
623	3.01	.923	1.03	3.16	105	.63	0.00	31.2
831	2.86	19.009	0.91	3.47	116	.66	0.00	20.3
1040	2.65	19.053	0.90	2.97	121	7.65	—	25.0
1308	2.38	.091	1.01	2.93	129	.66	—	20.4
1557	2.22	.121	1.23	2.83	133	.68	—	30.8
1786	2.05	.138	1.47	2.89	134	.72	—	—
2038	1.91	.158	1.89	2.79	134	.74	—	29.0
2538	1.66	19.181	2.60	2.69	132	7.81	—	32.0
3040	1.54	.192	3.05	2.65	127	.85	—	28.2
3291	1.52	.195	3.32	2.52	123	.88	—	—
3541	1.50	.197	3.33	2.48	123	.89	—	30.2
3793	1.48	.199	3.46	2.47	123	.90	—	—
4044	1.46	19.201	3.56	2.41	121	7.90	—	31.0
4546	1.49	.203	3.67	2.35	123	.90	—	29.8
5048	1.54	.204	3.73	2.41	120	.88	—	30.6

St. H_{14-B} (Ry 1989). 40°00'N, 144°08'E. May 4, 1964. Depth-5315m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	10.6	18.791	7.08	0.55	14	8.10	0.20	4.2
50	8.22	.772	6.53	0.78	18	.14	0.20	6.6
100	7.18	.706	6.42	0.88	20	.11	0.05	6.6
150	6.99	.677	6.57	0.88	19	.11	0.05	7.2
200	6.15	.631	6.64	0.98	23	.10	0.05	8.9
300	4.02	18.516	6.54	1.40	33	8.04	tr	11.5
400	3.68	.601	4.71	1.93	50	7.91	tr	16.2
500	4.00	.720	3.35	1.80	65	.78	tr	24.2
600	3.83	.804	2.43	2.52	79	.73	0.00	23.2
800	3.54	.943	1.23	2.66	101	.65	0.00	37.2
1000	3.10	19.018	1.10	2.63	116	7.62	—	25.8
1250	2.75	.064	0.98	2.70	126	.62	—	32.8
1500	2.44	.101	1.13	2.86	133	.65	—	34.1
1757	2.15	.132	1.46	2.84	138	.67	—	—
2009	2.00	.151	1.84	2.76	139	.67	—	38.6
2514	1.72	19.176	2.54	2.40	134	7.74	—	35.5
3018	1.60	.190	2.96	2.39	132	.79	—	28.0
3271	1.55	.194	3.26	2.40	127	.81	—	—
3523	1.52	.197	3.45	2.38	127	.83	—	30.7
3775	1.49	.199	3.47	2.40	127	.85	—	—
4028	1.47	19.201	3.56	2.28	125	7.87	—	21.2
4532	1.49	.202	3.75	2.28	120	.87	—	27.0
5537	1.53	.203	3.81	2.28	116	.87	—	29.8

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St. H₁₇ (Ry 1990). 42°02'N, 149°35'E. May 14~15, 1964. Depth-5140m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	6.7	18.354	8.26	0.88	5	8.25	—	—
55	4.82	.499	7.31	1.55	27	.16	—	—
110	3.38	.476	6.82	1.70	34	.11	—	—
165	4.31	.616	5.11	2.10	40	.03	—	—
220	3.13	.614	3.66	2.55	62	7.88	—	—
288	3.49	18.722	2.79	2.78	70	7.78	—	—
386	3.50	.786	1.93	2.85	80	.73	—	—
484	3.51	.871	1.46	3.00	99	.72	—	—
582	3.37	.922	1.17	3.02	100	.67	—	—
780	3.04	.994	0.98	3.09	112	.67	—	—
1081	2.63	19.059	0.95	3.36	125	7.69	—	—
1327	2.34	.090	1.13	3.04	131	.73	—	—
1574	2.18	.123	1.35	3.26	140	.74	—	—
1810	2.01	.135	1.62	3.21	137	.77	—	—
2044	1.86	.158	2.00	3.03	133	.79	—	—
2522	1.66	19.176	2.61	2.90	130	7.83	—	—
3007	1.55	.187	3.05	2.86	127	.88	—	—
3251	1.52	.191	3.31	2.69	126	.91	—	—
3497	1.49	.194	3.35	2.71	126	.91	—	—
3742	1.48	.197	3.45	2.73	123	.91	—	—
3989	1.47	19.198	3.53	2.65	123	7.91	—	—
4485	1.50	.198	3.68	2.56	123	.90	—	—
4980	1.54	.201	3.72	2.58	128	.90	—	—

St. H₁₈ (Ry 1991). 42°04'N, 151°45'E. May 15, 1964. Depth-5070m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	8.8	18.587	7.15	1.22	20	8.22	—	—
45	8.10	.703	7.02	1.16	21	.23	—	—
62	5.94	.644	6.86	1.77	32	.11	—	—
139	5.40	.586	6.51	1.48	26	.17	—	—
193	5.26	.633	5.73	1.50	25	.17	—	—
194	3.92	18.571	5.60	2.07	39	8.09	—	—
262	3.20	.627	3.74	2.69	57	7.88	—	—
329	3.44	.719	2.76	3.07	69	.83	—	—
397	3.57	.796	2.07	3.26	80	.78	—	—
533	3.60	.899	1.39	3.37	95	.75	—	—
670	3.29	18.951	1.10	3.30	101	7.73	—	—
849	2.96	19.003	1.02	3.41	111	.73	—	—
1065	2.69	.055	0.92	3.59	123	.73	—	—

H. Katsuura, H. Akamatsu, T. Akiyama: Preliminary Report of the Japanese Expedition

St. H₁₉ (Ry 1992). 42°08'N, 153°56'E. May 17, 1964. Depth-5375m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	7.9	18.674	7.19	0.83	22	8.20	—	—
54	7.61	.692	7.01	0.96	24	.20	—	—
108	6.60	.736	6.80	1.16	23	.17	—	—
162	6.46	.736	6.69	1.18	21	.16	—	—
216	6.08	.737	5.85	1.39	27	.13	—	—
327	4.47	18.737	3.43	2.19	57	7.94	—	—
437	4.19	.814	2.41	2.49	71	.83	—	—
546	3.98	.871	1.75	2.67	84	.75	—	—
655	3.65	.929	1.24	2.84	94	.72	—	—
874	3.08	.931*	0.92	2.82	112	.71	—	—
1093	2.76	19.051	0.90	2.94	119	7.72	—	—
1367	2.44	.090	1.00	2.91	123	.73	—	—
1642	2.22	.118	1.23	2.84	139	.73	—	—
1760	2.11	.132	1.41	2.95	133	.75	—	—
2008	1.96	.153	1.75	2.88	133	.76	—	—
2504	1.72	19.176	2.43	2.64	126	7.82	—	—
3001	1.59	.191	2.91	2.62	126	.85	—	—
3249	1.55	.195	3.10	2.39	123	.93	—	—
3498	1.52	.199	3.26	2.51	122	.90	—	—
3747	1.50	.201	3.39	2.49	119	.90	—	—
3996	1.49	19.202	3.50	2.49	123	7.90	—	—
4495	1.50	.204	3.64	2.27	118	.90	—	—
4994	1.54	.207	3.70	2.24	118	.90	—	—

* value doubtful

St. H₂₀ (Ry 1993). 42°08'N, 155°56'E. May 18, 1964, Depth-5505m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	7.7	18.628	7.15	1.16	30	8.12	—	—
49	5.26	.568	7.00	1.33	28	.13	—	—
98	5.78	.656	6.91	1.39	35	.11	—	—
147	6.04	.700	6.70	1.40	27	.12	—	—
196	5.56	.686	6.30	—	35	.10	—	—
316	3.73	18.697	3.32	2.53	64	7.89	—	—
420	3.97	.818	2.19	2.75	79	.78	—	—
525	3.84	.882	1.50	2.89	92	.73	—	—
630	3.55	.925	1.09	2.97	100	.69	—	—
845	2.99	.990	0.79	2.97	119	.68	—	—
1066	2.75	19.043	0.82	3.12	124	7.67	—	—
1350	2.39	.088	0.99	3.14	137	.69	—	—
1641	2.20	.126	1.25	3.14	144	.70	—	—
1644	2.20	.122	1.24	2.98	142	.72	—	—
1873	2.03	.144	1.59	2.78	142	.74	—	—
2336	1.79	19.169	2.15	2.69	139	7.75	—	—
2811	1.63	.185	2.68	2.64	140	.79	—	—
3051	1.58	.190	2.88	2.44	131	.85	—	—
3296	1.55	.194	3.12	2.60	126	.88	—	—
3541	1.51	.197	3.26	2.50	128	.87	—	—
3787	1.49	19.198	3.38	2.48	127	7.88	—	—

St. H₂₁ (Ry 1994). 41°52'N, 157°38'E. May 21, 1964. Depth-5565m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	8.4	18.730	6.49	0.73	21	8.17	—	—
57	7.63	.748	6.62	0.98	21	.19	—	—
114	6.44	.708	6.77	1.07	24	.16	—	—
171	5.90	.690	6.62	1.23	25	.16	—	—
230	5.83	.725	5.36	1.46	32	.08	—	—
333	4.37	18.743	3.28	2.27	57	7.87	—	—
445	3.98	.811	2.25	2.47	78	.78	—	—
559	3.77	.879	1.47	2.70	91	.73	—	—
674	3.48	.936	1.11	2.83	100	.70	—	—
906	3.05	19.016	0.89	2.88	112	.70	—	—
1139	2.68	.064	0.92	2.85	123	7.69	—	—
1433	2.35	.102	1.04	2.71	134	.70	—	—
1730	2.17	.130	1.36	2.83	136	.73	—	—
1747	2.11	.132	1.42	2.85	139	.73	—	—
1995	1.94	.152	1.76	2.71	135	.75	—	—
2490	1.71	19.176	2.23	2.59	133	7.81	—	—
2987	1.59	.187	2.89	2.47	126	.85	—	—
3236	1.55	.190	3.10	2.27	127	.93	—	—
3485	1.52	.193	3.27	2.47	130	.92	—	—
3735	1.50	.197	3.38	2.43	125	.91	—	—
3984	1.49	19.197	3.49	2.59	123	7.91	—	—
4485	1.51	.198	3.61	2.60	125	.90	—	—
4986	1.54	.203	3.68	2.49	126	.91	—	—

St. H₂₂ (Ry 1995). 41°59'N, 159°58'E. May 22, 1964. Depth-5660m.

Depth (m)	T (°C)	Cl (‰)	O ₂ (ml/l)	PO ₄ -P (μg-atoms/l)	Si (μg-atoms/l)	PH	NO ₂ -N (μg-atoms/l)	NO ₃ -N (μg-atoms/l)
0	9.3	18.813	6.79	2.75	14	8.20	—	2.4
53	8.65	.803	6.68	0.92	14	.21	—	2.4
108	7.07	.745	6.78	1.08	18	.21	—	3.2
164	7.10	.780	6.41	1.34	20	.18	—	3.0
222	6.54	.761	5.86	1.33	25	.15	—	6.4
304	5.52	18.766	3.86	2.15	43	8.00	—	24.2
408	4.49	.795	2.75	2.48	58	7.85	—	29.0
516	4.21	.863	1.91	2.77	71	.80	—	25.4
624	3.77	.920	1.39	2.88	90	.74	—	27.5
844	3.24	.986	0.93	3.05	101	.72	—	14.2
1071	2.84	19.039	0.83	2.97	116	7.70	—	10.4
1359	2.47	.084	1.01	2.93	124	.70	—	9.0
1652	2.24	.117	1.25	2.98	129	.73	—	8.0
1737	2.12	.131	1.49	2.97	125	.72	—	9.2
1972	1.97	.146	1.71	2.88	126	.76	—	8.0
2446	1.73	19.171	2.42	2.77	126	7.82	—	9.7
2924	1.60	.184	2.90	2.63	120	.85	—	—
3163	1.56	.187	3.04	2.56	123	.91	—	6.5
3404	1.54	.192	3.23	2.52	123	.90	—	7.1
3646	1.52	.195	3.32	2.50	124	.89	—	8.8
3888	1.50	19.197	3.42	2.50	125	7.89	—	8.6
4375	1.51	.200	3.58	2.57	124	.89	—	8.5
4864	1.53	.201	3.70	2.43	119	.91	—	7.3

気 象 庁

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